Mathematical modeling of melting rate in twin-wire welding

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Abstract

The paper treats four mathematical models for calculation of melting rate in arc fusion welding with a wire in coil form. The mathematical models permit calculation of melting rate in direct current welding with single-wire and double-wire electrodes (both polarities). For single-wire welding the models treated have been improved with regard to the ones published in the literature, for twin-wire welding, these are the first models for calculation of melting rate. The mathematical models have already been tested in practice and the results obtained show that they are very accurate, simple and applicable to practice. © 2000 Elsevier Science S.A. All rights reserved.

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1. Introduction

Single-wire welding is characterized by a contact tube through which two wires are fed simultaneously. Both may have the same speed, a joint feed drive mechanism and regulation and a single power source. The wires may be arranged one after another or one beside the other with regard to the welding direction. The distance between the wires may be optional and depends on the application (welding, surfacing) (Fig. 1). Submerged arc welding with the twin-wire electrode has been known in practice for several decades [1,2]. Twin-wire gas-shielded arc welding in gas mixtures has been gradually introduced into practice for the last decade [3–5]. Although twin-wire welding is used in practice and has numerous advantages over single-wire welding, it has almost not been investigated.

Development of a mathematical model for prediction and calculation of melting rate in welding with a twin-wire electrode is a study on which it has not been reported in the literature yet.

2. Literature review

Data found in the literature show that there are many scientific researchers who have studied the melting rate in single-wire welding. Some of them elaborated an equation or a model for predicting melting rate. Two different methods are known. In the first case scientific researchers made a number of experiments and the results obtained were processed statistically [6–8]. In the second case mathematical models were based on physical rules applying to metal arc welding [9–11]. The majority of the researchers adopted a middle course, proceeded from physical simplifications of certain physical phenomena, and obtained an approximate mathematical model by means of statistical processing of the experimental results obtained.

The first extensive study of melting rate in single-wire welding in various shielding media was carried out by Wilson et al. [12]. He performed an extremely great number of experiments in a very wide range of parameters. On the basis of the experimental results he elaborated an equation for prediction of melting rate.

Regarding the present state of knowledge of the melting process, his equation is not sufficient anymore. It does not take into consideration the kind of current, polarity, the type of power source, and the type of shielding medium used.

A basic study of metal-arc welding of various metals in various shielding gases was performed by Lesnewich [13].
He studied the arc, its effects on anode and cathode heating, the influence of the electrode diameter, the wire extension, polarity and the type of shielding gas as well as the effect of the chemical composition of an electrode on melting rate. He found that anode heating depended on the electrode diameter and welding current intensity; but it was dependent neither on the wire extension length, the type of shielding gas applied nor on the chemical composition of the electrode. Cathode heating is affected by the chemical composition of the shielding gas applied and that of the electrode wire. An increase in the wire extension length increases the temperature in the wire extension as well as electron emission, which reduces the number of positive ions. This causes cathode heating to reduce. Owing to complicated physical and chemical phenomena at the cathode, the influence of the electrode diameter on cathode heating cannot be proved.

Taking into consideration all the influences, Lesnewich arranged an empirical equation which mathematically predicts the melting rate with d.c. electrode positive and for low-alloy steels (Eq. (1)):

\[
M = 7.72 \times 10^{-3} + 0.13d^2I + 2.28 \times 10^{-8} \frac{L^2}{d^{3.8}}
\]

where \( I \) (A) is the welding current intensity, \( L \) (mm) the wire extension and \( d \) (mm) is the wire diameter.

Robinson [14] corrected Wilson’s equation on the basis of experimental results obtained. He showed these results in a log–log diagram as depending on current intensity and other parameters. By means of the curves he recorded mathematical equations for prediction of melting rate with d.c., electrode positive and electrode negative.

The mathematical equations for prediction of melting rate were also treated by Jackson [15].

A similar method was used by Chandel [8]. In his article he reports on mathematical models for prediction of melting rate in d.c. submerged arc welding with electrode positive and electrode negative and in a.c. welding. The mathematical models are based on statistical processing of practical results obtained. Although in the article numerous wrong suppositions may be found, which was noticed also by Lesnewich [16], the models are quite a true picture of the experimental results and applicable in practice, primarily to filler materials used by the author.

A somewhat different record and prediction of melting rate can be found with Demjancević [17] who presents a mathematical model for calculation of d.c. melting rate for a constant wire diameter and for both polarities, which is, of course, unusual and leads to inaccurate results (Eq. (2)):

\[
M = 6.3 + \frac{70.2 \times 10^{-3}}{d^{1.35}}I
\]

where \( d \) (mm) is the wire diameter and \( I \) (A) is the welding current intensity.

A very simple mathematical model for calculation of melting rate was given by Stenbacka and Persson [18]. The equation takes into consideration only welding current and wire extension length, which means that it is valid for one wire diameter alone.

Quite a different way of elaboration of a mathematical model for prediction of melting rate in gas-shielded metal-arc welding was used by Halmoj [10] and Waszink and van den Heuvel [19]. They proceeded from physical rules of wire extension heating. Knowing the functional dependence of specific electric resistance on temperature \( \rho = f(T) \) and of heat contained on temperature \( H = f(T) \) for a certain filler material, they established simple equations for prediction of melting rate. The equations derived by the authors mentioned are of a very general character. Certain coefficients in the equation should be determined for each kind of filler material and for each electrode diameter separately.

3. Elaboration of a mathematical model for melting rate

Influences of welding parameters on melting rate in single wire and twin wire submerged arc welding were studied during numerous experiments. Melting rate depends mostly on welding current intensity, polarity, the electrode diameter and the wire extension length. In multiple-wire electrode welding, it depends also on the number of wires applied and the distance between them. The other welding parameters, i.e. welding speed, arc voltage, kind of shielding medium, type of welding current source, chemical composition of the filler material (valid for low-alloy steels) etc., have little influence. The majority of these parameters have been studied, their influence is known and in our judgment, they may be neglected.

3.1. Influence of welding current intensity on melting rate

A study of the influence of current intensity on melting rate was carried out by means of practical experiments. The results obtained are shown in Figs. 2 and 3. Fig. 2 shows the influence of welding current on melting rate in welding with
a single wire and a twin wire having a diameter of 3 mm. Welding was carried out also with wire diameters of 1.2, 1.6 and 2.0 mm. The results for the twin wire are shown in Fig. 2 ($L$ is the wire extension length and $b$ is the distance between the wires).

Based on both diagrams (Figs. 2 and 3) similar conclusions may be drawn. In all cases the melting rate increases slightly exponentially with an increase in welding current intensity.

3.2. Influence of the electrode diameter on melting rate

A study of the influence of the electrode diameter on melting rate substitutes, with some authors, for a study of the influence of welding current density. This substitution is possible in order to perform a superficial estimation, but in an accurate analysis, particularly in submerged arc welding, such a substitution is not allowable. Welding current is conducted through the wire extension also on its surface. In submerged arc welding, where the wire is dipped into flux during welding, this plays an important part. The experimental results regarding the influence of the electrode diameter on melting rate are shown in Figs. 3 and 4.

Even an inaccurate estimation of the influence of the electrode diameter on the melting rate shows that this is a rational fractional function and that the number of wires used has no important influence on the form of functional relation. In twin-wire electrode welding (3 mm wire), melting rate is by 30–35% lower than with a 1.2 mm wire with equal current intensity per wire.

3.3. Influence of the wire extension length on melting rate

The wire extension length plays a very important part in arc welding. The welding process itself, weld geometry and melting rate can be affected by changing the wire extension length.

The influence of the wire extension length on melting rate in welding with a 3 mm wire and current intensity of 400 A per wire was determined by practical experiments. The results are shown in Fig. 5.
The results obtained (Fig. 5) show that the relationship between the wire extension length and the melting rate in single-wire welding is linear, which is in agreement with a physical law. An accurate measurement of the wire extension length proved to be a problem in the study of the influence of the wire extension length on the melting rate. Measurement of the wire extension carrying welding current is a very difficult task even in open-air welding, but in submerged arc welding it is still less possible. The first problem is that a part of the wire extension length is covered by flux, and the second that the wire is constantly melting in droplets during welding, therefore, an error in the accurate measurement can be of the size of a droplet.

In the literature various more or less accurate methods of establishment of the wire extension length can be found. Tihodeev [20] used an X-ray camera, with which he could determine the wire extension length and the arc length in single-wire submerged arc welding very accurately.

Measurement of the wire extension length was very much simplified by Chandel [8]. He took the distance between the contact tube and the workpiece as the wire extension length in mathematical models for the calculation of the melting rate in submerged-arc welding.

In gas-shielded metal-arc welding, Halmøj [10] recorded the welding process and the wire extension length on a film. He considered the distance between the contact tube and the wire extension tip, which had not melted yet, as a real value. That is to say that, if at the moment of measurement there was a droplet at the wire tip, it was not added to the whole length.

Similar procedures can be found in the papers by Amson [21] and Villeminot [22].

Considering the fact that welding current is not conducted from the contact tube to the wire only at the nozzle tip but also at a larger part of the nozzle, Waszink and van den Heuvel [19] added another 1.25 mm to the “normal” wire extension length in gas-shielded arc welding with a 1.2 mm wire.

In our studies the wire extension length was measured in several ways. The most accurate measurement seemed to be the one carried out with an apparatus shown schematically and described by Tušek [23,24].

3.4. Elaboration of a mathematical model for melting rate based on practical results

On the basis of functional influences of the above-mentioned parameters established experimentally, a uniform model was to be elaborated which would include the three parameters which are most important to melting rate. Considering the fact that it is very difficult to mathematically describe the influence of polarity and to a certain extent also the influence of the number of wires used, the first mathematical models for calculation of melting rate will be elaborated for single-wire and twin-wire welding and for both polarities separately.

For the experimental study, a plan of practical experiments was set. An extremely large number of experiments were carried out in a wide range of welding parameters including repetitions in those parameters which gave favorable and practically applicable results. Statistical data processing embraced all the specimens and those results which are applicable to practical cases.

A general mathematical model as stated in Eq. (3) was elaborated by means of physical laws of filler material melting by the arc and of the wire extension heating due to ohmic heating. The model is established on physical basis and has two constituent parts. The first describes the contribution of arc energy to heating of the neighboring arcs and wires, and the second the contribution of a higher temperature of the wire extensions due to stronger electric resistance and higher heat energy input to the melting rate

\[ M = a_0 + a_1I + a_2 \frac{P^2L}{d^2} \]  

(3)

where \( a_0, a_1, \) and \( a_2 \) are constants.

The parameters in Eq. (3) and quantities in all the subsequent models will be expressed in the following units: \( M \) (kg/h), \( I \) (A per wire), \( L \) (mm), and \( d \) (mm).

In the elaboration of the models, a multiple regression analysis was used. The mathematical models were elaborated by means of the method of the smallest square deviation sum which permits unpartial evaluation to be made. The models consist of one dependent variable and two independent variables. In this case the first independent variable is \( I \) and the second \( P^2L/d^2 \).

For model calculations according to Eq. (3) a computer language PASCAL was used. The latter permitted to calculate 100 different values for the first and the second independent variable. Beside the coefficients \( a_0, a_1 \) and \( a_2 \) also the multiple regression coefficients and the standard deviation were calculated.

3.4.1. Welding with a single-wire electrode

In single-wire submerged arc welding wires having a diameter of 1.2, 1.6, 2.0 and 3.0 were used. With a 1.2 mm wire current intensity varied from 80 to 350 A per wire, with a 1.6 mm wire from 80 to 400 A, with a 2.0 mm wire from 80 to 600 A and with a 3.0 mm wire from 150 to 800 A. Welding was carried out with a common wire extension; this is 10 times the electrode diameter, and with an elongated wire extension, which is 40 times the electrode diameter.

Also in the above-mentioned range of welding parameters a plan of experiments were made and in the statistical analysis, those values were considered which gave impartial evaluation. The statistical method of the smallest square deviations was applied and 100 different specimens were considered to obtain a mathematical model for single-wire welding with electrode positive in the following form (Eq. (4)):
where $r = 0.9889$, $S_e = 0.327$.

The multiple regression coefficient $r$ is very high, which shows a favorable relationship between dependent and independent variables. The standard error ($S_e$) is within admissible limits.

A similar procedure was applied to single-wire submerged arc welding with electrode negative.

The mathematical model which describes the melting rate in single-wire welding with an electrode negative is given by Eq. (5):

$$M = 0.01384I - 0.407 + 1.9626 	imes 10^{-6} \frac{I^2L}{d^2}$$

where $r = 0.9876$, $S_e = 0.406$.

The multiple regression coefficient and the standard error show somewhat lower values due to larger dissipation of the experimental results in welding with electrode negative.

A comparison of the models for calculation of the melting rate in single-wire arc welding with electrode positive and with electrode negative confirms the previously established facts. It is evident that the coefficient in Eqs. (4) and (5) representing a part of the arc energy is higher in electrode negative welding than in electrode positive welding. The opposite is valid for the part of the model describing the energy distribution due to electric resistance of the wire extension.

3.4.2. Twin-wire welding

The number of experiments carried out with twin electrode was somewhat higher than in single-electrode welding. The range of parameters, particularly welding current intensity, was larger in twin-wire welding than in single-wire welding due to the heat processes going on between the arcs and the wires in twin-wire welding which permit welding with lower current intensity per wire. The wire extension length used with the twin wire was the same as with the single wire. The distance between the wires was determined on the basis of previous practical experiments. The results showed that an optimum distance between the wires can be determined by Eq. (6):

$$b = 1.2(d + 4) \pm 1$$

where $b$ (mm) is the distance between the wires and $d$ (mm) is the wire diameter. The distance between the wires is, in fact, the distance between the axes, i.e. central lines, of the two wires.

In the literature we have not found any study which would treat, in full, optimum and limit values of the distance between the wires regarding wire diameters and the welding process. The majority of authors gives the distance between the wires with regard to a certain wire diameter with which the experiments were carried out, or they merely recommend a certain distance for a certain case. For example, Probst et al. [25] recommend that in the case of a wire-electrode diameter of 1 mm in twin-wire gas-shielded welding the distance should not be shorter than 5 mm.

In a report by Akulov et al. [26] the influence of the distance between wires on the formation of the root pass and welding speed was studied. The optimum value for the distance between the wires is not stated.

More data can be found in an article by Spicin [27], where it is recommended that the distance between wires in twin-wire CO$_2$ welding with a 1.6 mm wire should vary between 2.5 and 8 mm. Neither does Killing [5] state any concrete data on the distance between wires.

Our studies showed in practice that a minimum distance between the wires should be 5 mm since with shorter distances, due to strong electromagnetic forces, undercut occurs and the appearance of a weld surface is less favorable. With a distance longer than 10 mm and with thinner wires, the heat effects between the wires and the arcs decrease, the welding cavity changes its shape, for a uniform cavity the energy is too low and with low current intensities three separate welding cavities may be obtained.

On the basis of these statements Eq. (6) was worked out. Yet it can be applied only to welding, i.e. to the wires arranged one after another with regard to the welding direction, and wire diameters from 1.2 to 3.0 mm.

A mathematical model describing melting rate in twin-wire welding with electrode positive is given by Eq. (7):

$$M = 0.02393I - 0.739 + 3.6093 \times 10^{-6} \frac{I^2L}{d^2}$$

where $r = 0.9805$, $S_e = 0.514$.

Eq. (8) gives a mathematical model for prediction of the melting rate in twin-wire arc welding with electrode negative:

$$M = 0.03193I - 0.876 + 3.0984 \times 10^{-6} \frac{I^2L}{d^2}$$

where $r = 0.985$, $S_e = 0.605$. Here again a similar comparison of the model dependent on polarity can be made as it was made of models for single-wire welding. The findings are similar. The share of arc energy in filler material melting is greater with twin-wire electrode negative than in electrode positive welding. Regarding the fact that arc energy melts more filler material in electrode negative welding, a higher welding speed is required. This results in lower heating of the wire extension and by this affects the energy share due to ohmic resistance.

The influence of the second wire in twin-wire welding on melting rate is more difficult to determine. In both models for twin-wire welding, an increase in all coefficients is evident but the extent of increase in individual coefficients is different.

The coefficient $a_1$ representing arc energy increases by more than twice in twin-wire welding. A conclusion can be drawn that a mutual influence of the arcs is quite strong and consequently melting rate is also high. The coefficient $a_2$ is
higher in twin-wire welding than in single-wire welding by less than twice.

This statement can be explained by the fact that arc energy melts more filler material per wire in twin-wire welding than in single-wire welding. With the same welding parameters this requires a higher wire feed speed in twin-wire welding. This results in lower heating of the wire extension.

4. Comparison of the theoretical and practical results obtained

The theoretical mathematical models have already been tested by experiment. The results obtained are shown in Figs. 6 and 7.

The comparative diagram in Fig. 6 shows the relationship between the measured value of melting rate and the one calculated by means of Eqs. (5) and (8). The comparison is valid for single-wire and twin-wire welding with electrode negative, it is evident from the diagram that the relationship between the theoretical and experimental results is favorable, which derives also from the value of the multiple regression coefficient and the value of standard deviations (Eqs. (5) and (8)). Some other characteristics are also evident from Fig. 6. The calculated values of melting rate in single-wire welding arc, in the case of low values of melting rate, lower than the measured ones but in the case of the higher values of melting rate the situation is reversed. For twin-wire welding it can be stated that the relationship is very favorable in the total range.

The diagram in Fig. 7 gives a comparison between the calculated and measured values of melting rate in single-wire and twin-wire arc welding with electrode positive.

It is evident from the diagram that there is a great deal of similarity. In single-electrode welding the deviation is greatest, i.e. 18%. But the average deviation is much smaller since Eq. (4) shows that the standard deviation is 0.327. In twin-wire welding deviations from the expected value are stronger, which is evident also from the value of the standard deviation (Eq. (7)).

5. Conclusions

A more elaborate mathematical model than the one existing before was developed for calculation of melting rate in single-wire arc welding. Additionally a mathematical model for calculation of melting rate in twin-wire arc welding not known from the literature before was developed.

On the basis of verification of validity of the mathematical models developed for single-wire and twin-wire arc welding it can be stated that the models are quite a true representation of the experimental results and that they are applicable to practical cases as well as to further research work.

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