ANALYSIS OF POSSIBILITY TO APPLY MATHEMATICAL MODELS OF ELEMENT TRANSITION IN ARC WELDING

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Abstract. The paper addresses mathematical models of element transition into overlaying metal and weld metal in different methods of arc welding: stir welding, welding taking account the transition coefficients, empirical, kinetic, and thermodynamic welding. Their comparative analysis is made, their advantages, disadvantages as well as various applications are demonstrated. The approach to creation of mathematical models of manual arc welding with coated electrodes and flux cored wire, based on the method of complete material balance, is grounded.

Key words: arc welding, mathematical modeling, forecasting, composition of weld metal.

Introduction

The current trends in science and technology are characterized by development, introduction, and wide use of different models created both on the basis of the traditional experimental approach and with application of up-to-date information technologies [1]. One of the main stages of welding technology development is calculation of the composition of weld metal or overlaid metal. The composition of weld or overlaying metal and its properties are the result of complex thermal, physicochemical processes, and the process of thermal deformation. Their quantitative description is difficult due to transience of the welding process, heterogeneity of thermal fields, presence of a multitude of phases interacting chemically, and complex hydrodynamic conditions. As of today the approaches to estimation of the metal composition are as follows: stir calculation, calculation taking account the transition coefficients, regression equations, calculations using thermodynamic or kinetic models [2-5].

Topicality

Development of methods for predicting the chemical composition of weld metal gives the opportunity to optimize the welding process at the design stage by selection of welding materials and the parameters of modes which provide specified features of a welded joint. Development of the models are also important theoretically inasmuch as the proximity of calculated and empirical data is an indication of the compliance of the accepted analytical model to the picture of physical interaction of phases during welding, surfacing and deposition processes.

Problem Statement

Consider the existing models that allow forecasting the composition and properties of overlaid metal and weld metal forming in the process of arc welding.

Theory

Methodologically two main approaches to mathematical simulation of complex systems can be distinguished: the “black box” method [1, 6] and the analytical method [1, 7, 8]. Models developed to describe arc welding process and using the “black box” method, are the ones based on stir calculation of weld metal and those taking into account transition coefficients, regression equations. The analytical method is used in models based on thermodynamic and kinetic analysis.

The simplest method to estimate the composition of overlaying metal and weld metal is stir calculation (1) [9].

$$[E_i]_{weld} = [E_i]_{base} \cdot \gamma_{\text{base}} + [E_i]_{\text{filler.}} \cdot (1 - \gamma_{\text{filler}}), \qquad (1)$$

where $[E_i]_{\text{weld}}$ is the content of an element in the metal of a weld (in overlaying metal), mass %; $[E_i]_{\text{base}}$ is the content of an element in the base metal, mass %; $[E_i]_{\text{filler.}}$ is the content of an element in the filler metal (in a typical overlaying metal), mass %; γ_{base} is the share of the base metal in the metal of a weld (in the overlaying metal).

In this case it is required to know the content of the base metal, the typical composition of the overlaying metal, and the share of the base metal. The typical compositions of the base and overlaying metal are defined in reference documents and their shares are determined approximately. It is due to the fact that the share used in calculations can be in disagreement with the actual one because of mode parameters change. Thus this method gives approximate result, but it is very suitable for preliminary estimation. It can be used to solve both direct (calculation of weld metal composition) and inverse (welding material choice) problems for all the methods of arc welding.

One of the most common methods to estimate the composition of weld metal and overlaying metal is calculation taking into account transition coefficients. To make it one needs the data used for stir calculation, the only difference is that the content of an element in a weld (overlaying metal), obtained by stir calculation, is corrected with the element transition coefficient. The transition coefficient is the fraction of the element mass, transferred to the metal of the weld (metal welded over) during welding (overlaying). The transition coefficient of an element depends on its initial quantity in welding materials, as well as on the reactions proceeding at all the stages of welding. This method can be used to estimate the transition of one element during arc welding. In this case the influence of process variables and other element concentrations in welding materials on the transition coefficient is not virtually analyzed [10]. This technique can be used for all methods of arc welding except argon-arc welding since in this case the coefficients of element transition into overlaying metal are almost equal to 1 because of lack of oxidation processes, and the content of the elements may be estimated by stir calculation.

In some works [2, 11] regression equations were obtained which describe the dependence of the composition of weld metal on some parameters of a welding mode. However regression equations express the dependence of some values on one or two parameters. But it is not enough to create a full-fledged mathematical model. Models based on processing of experimental data do not possess the main, from our point of view, conditions for applications, that is versatility and precision.

The development of mathematical models of the interaction processes during arc welding, using the analytical approach, assumes considering their physicochemical regularities based on fundamental laws of thermodynamics and chemical kinetics [12 - 19].

Arc welding in active shielding gases is one of the widespread kinds of fusion welding. At that a number of physicochemical processes take place that determine the composition and properties of weld metal. Simulation of the processes on the basis of calculation methods gives the opportunity to predict the chemical composition of the weld, properties of a welded joint depend on.

Initially the thermodynamic model of the processes of welding in gases was developed [12]. Comparison of experimental and calculation data obtained by using the thermodynamic model showed that equilibrium is not attained for reactions in which elements with great sensibility to oxygen (*C*, *Al*, *Ti*) participate because the estimated values of the concentrations are much less than the experimental ones. In this connection the conclusion was made concerning the necessity to take into consideration kinetic decelerations of chemical reactions during welding in gases. In the welding zone two successive stages of interactions of metal with gas and slag are usually distinguished: the stage of drop on electrode and that of bath. The stages differ greatly by temperature, the convection conditions, and the interaction surface [20]. According to some authors [13] the interaction of the superheated metal of electrode drops in the leading part of the bath at the bottom of the arc (the “hot” part of the bath) should be considered as the first stage. As shown in [1] it is rather difficult to allot the share of individual stages in the overall interaction. In particular the mechanism of oxygen transfer from the arc atmosphere into metal is not clear: by dissolution in the metal with the consequent interaction with elements in the bulk or on the metal-slag border or by formation of FeO or other elements oxides. The role of metal evaporation and formation of volatile SiO, AlO and other oxides is unknown. Taking into account kinetic limitations for several phase interaction schemes allowed uncovering the most possible mechanism for the processes and predicting the content of majority alloying constituents in weld metal with satisfactory accuracy.

It is known that in manual arc welding and hidden arc welding there is no equilibrium between metal and slag in most cases[4, 21]. Therefore in models based on thermodynamic approaches calculation results do not correspond to experimental ones.

In this connection in [13, 14] a mathematical model was described reflecting the kinetics of chemical reactions of hidden arc welding, that allows predicting the weld composition taking into account the following process features:

- the interaction between metal and slag includes two successive stages – the stage of electrode (drop) and that of bath, which differ by temperature, geometry, and hydrodynamic conditions;
- continuous renewal of interacting metal and slag masses at every stage as a result of melting and crystallization of adding and base metal and flux;
- presence of electrolysis during bypassing part of current by liquid slag;
- coincidence of all the reactions at every stage and their mutual thermodynamic and kinetic influence;
- influence of diffusion resistance of all the agents in metal and slag on the rate of each reaction and dormancy of the chemical act of ion discharge in the metal-slag border.

This mathematical model is a an equation system that allows calculating the rate of phase interaction and, thereupon, the composition of metal and slag. Such equations can be written for each element [15]. The model built allows predicting the composition of overlaid metal including its change along the length of overlaying layer when different disturbances take place: weld transfer onto base metal of another brand, crossing welds put before, fluctuation of process variables etc.

At the same time the model includes some simplifying assumptions:

- the chemical composition of metal and slag at each stage at a given point in time within a phase is identical (perfect mix);
- the interaction surface of metal and slag at each stage can be described by certain contact area and constant of mass exchange average in time;
- according to [9, 22, 23] influence of reactions with the gas phase, can be neglected to a first approximation, the only exclusion is the reaction with hydrogen and nitrogen participation [24].
- the temperature of reaction zones at the stages of drop and bath is in accordance with [24]: T_K = 2500 K (for alternative and direct current of reverse polarity), T_K = 2300 K (for direct current of straight polarity), T_B = 2070 K.

One feature of this mathematical model is worthy of being noted. Practical application of the model becomes considerably simpler, if dependences of input parameters on welding parameters are known, that is not always possible.

To develop a mathematical model of arc welding under ceramic flux some authors [19, 20] made the following assumptions:

- the reducing agent particles (carbon was used as the agent) or the particles of metal additive are of similar size and distributed uniformly in volume of a welding bath;

- initially the process of iron reduction takes place according to the reaction

$$C_{TB} + FeO = Fe + CO \quad (2)$$

a metal phase forms on the surface of a particulate;

- dissolution of carbon in iron continues up to saturation concentration is reached. Taking into account that when the concentration of carbon in iron increases the contact angle between Fe-C melt and solid carbon decreases sharply, and on the contrary the rate of spreading increases [25], suppose, that the particles formed are solid balls of carbon, surrounded by uniform film of $Fe\text{-}C_H$ melt;

- the rate of supply of additive particles and drops of electrode metal into welding bath is determined by the rate of their fall in slag which depends on the particle size, welding parameters, and hydrodynamic conditions in the welding zone;

- interaction with the gas phase was considered only when particles of solid carbon in flux were oxidized when the flux was heated

$$C_{TB} + ½ \{O_2\} = \{CO\}; \quad (3)$$

- interaction of metal and slag was described using a combination of reactions with common reagent, proceeding in all borders between phases,

$$1/m[Э_i] + (FeO) = 1/m(Э_iO_m) + [Fe]. \quad (4)$$

- metal and slag baths are reactors of perfect mix.

The calculation results and their comparison with experimental data [18, 19] shows the possibility to predict the phase composition in welding or overlaying under ceramic flux.

Conclusion

The analysis above shows that when definite conditions are met each method can be applied successfully. At the same time we can state that known physical models and methods of prediction of overlaying and weld metal composition either use data and correlations which are not reliable enough and are difficult to determine (the metal-slag contact area, drop temperatures, time and rate of phase interaction) or give semiquantitative results.

Thus it is necessary to prove and develop the method to estimate overlaying metal and weld metal composition on the basis of integral, systematic, and practical approach. One of the possible variants of the approach is the method of complete material balance.

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