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A new method to estimate heat source parameters in gas metal arc welding simulation process

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HIGHLIGHTS

- A new method for accurate simulation of heat source parameters was presented.
- The partial least-squares regression analysis was recommended in the method.
- The welding experiment results verified accuracy of the proposed method.

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ABSTRACT

Heat source parameters were usually recommended by experience in welding simulation process, which induced error in simulation results (e.g. temperature distribution and residual stress). In this paper, a new method was developed to accurately estimate heat source parameters in welding simulation. In order to reduce the simulation complexity, a sensitivity analysis of heat source parameters was carried out. The relationships between heat source parameters and welding pool characteristics (fusion width (W), penetration depth (D) and peak temperature (T_p)) were obtained with both the multiple regression analysis (MRA) and the partial least-squares regression analysis (PLSRA). Different regression models were employed in each regression method. Comparisons of both methods were performed. A welding experiment was carried out to verify the method. The results showed that both the MRA and the PLSRA were feasible and accurate for prediction of heat source parameters in welding simulation. However, the PLSRA was recommended for its advantages of requiring less simulation data.

1. Introduction

The gas metal arc welding (GMAW) is a kind of fusion welding process. All commercially important metals, such as carbon steel, stainless steel, aluminum and copper, can be welded with this process by choosing the appropriate shielding gas, electrode and welding condition [1]. As have been known, fusion welding of metals is a kind of process which includes a heating and a cooling cycle. The mechanical properties of a weld are significantly affected by quite a lot of factors (such as chemical–metallurgical reactions in the liquid metal, grain growth, solid state phase transformations, etc.) throughout the whole welding process. Those factors are controlled by thermal gradients and temperature fields during successive welding cycles inside different groove geometries [2]. However, it is difficult to quantify the thermal gradients and temperature fields by experimental work. Numerical simulation is a powerful tool in prediction of welding temperature field and residual stress. Due to the development of computer technology (softwares and hardwares), it is now possible to get satisfied results by using numerical techniques, for example finite element method (FEM) [3–5].

Although numerical simulation of welding processes still face with numerous challenges after having been developed over past several decades, some detailed analytical solutions and several models have been suggested for simulating welding heat sources [6]. Thereinto, the Goldak's double ellipsoidal heat source model as illustrated in Fig. 1 was widely used to depict the energy distribution in the GMAW simulation process [7].

According to the Goldak's model, energy distribution in a double ellipsoidal heat source was given as two parts:

For the front heat source:

$$q_f = \frac{6\sqrt{3} f_f Q}{abc_f \pi\sqrt{\pi}} e^{(-3x^2/a^2)} e^{(-3y^2/b^2)} e^{(-3z^2/c_f{}^2)} \quad (1)$$

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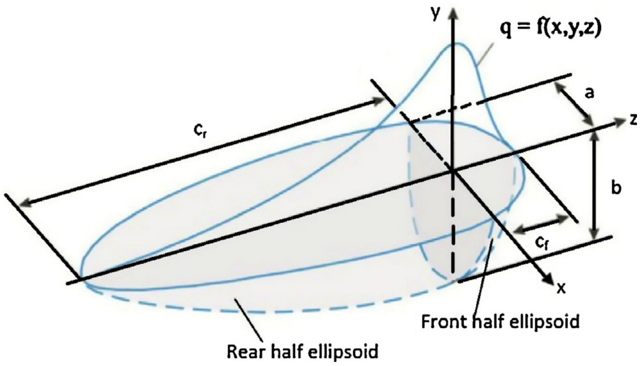

Fig. 1. Double ellipsoidal heat source model [7].

For the rear heat source:

$$q_r = \frac{6\sqrt{3}f_r Q}{abc_r\pi\sqrt{\pi}} e^{(-3x^2/a^2)} e^{(-3y^2/b^2)} e^{(-3z^2/c_r{}^2)} \quad (2)$$

$$Q = \eta IU \quad (3)$$

where x, y and z are the local coordinates of the double ellipsoid model as shown in Fig. 1. a, b and c are the semi-axes of the ellipsoid, c_f is the front part, and c_r is the rear part in the model, f_f and f_r represent the fraction of the heat deposited in the front and rear half ellipsoid, respectively. It was assumed that f_f was 1.5 and f_r was 0.5 according to the Ref. [8]. Q is the power of the welding heat source. It can be calculated with the welding current I and voltage U, which were precisely recorded by machine during welding. The arc efficiency of the GMAW η was assumed to be 0.8 according to the catalog of the welding machine used [1].

Reasonable thermal gradient and temperature fields can be obtained by adjusting the heat source parameters. However, the crux of the problem is how to accurately characterize the values of a, b, c_f and c_r before welding simulation. Usually, those heat source parameters were obtained from experience, which leaded to obvious simulation error. As welding is extremely sensitive to the control parameters of technological processes, some researchers tried to improve the way to precisely predict heat source model parameters, which made simulation results being connected with the actual welding characteristic for different processes [9]. Some significant studies investigated optimum process parameters selection via establishing a mathematical model correlating welding parameters with quality characteristics by using different approaches [10–12]. It should be noted that in the most published studies, the aims of researches were to get the mathematical models of characterizing the relationships between experimental welding parameters and simulation input parameters, which meant all the prediction models require large numbers of expensive and time-consuming welding experiments.

The multiple regression analysis (MRA) and some other algorithms were extensively used in parameter prediction of welding simulation [13,14]. The MRA can only solve linear problem with complete data, although it is quite effective and widely applied in practice. The partial least-squares regression analysis (PLSRA) is a novel multivariate data analysis method developed from the practical applications, which was mainly used for regression modeling between multi-dependent variables and multi-independent variables [15]. Moreover, compared with ordinary multiple regression methods, the PLSRA possesses many advantages, such as avoiding the harmful effects of multicollinearity and being capable of building the models when the number of observations is less than the number of variables, etc. [16]. In addition, the PLSRA effectively integrates the basic functions of regression model, principal components analysis and canonical correlation analysis. However,

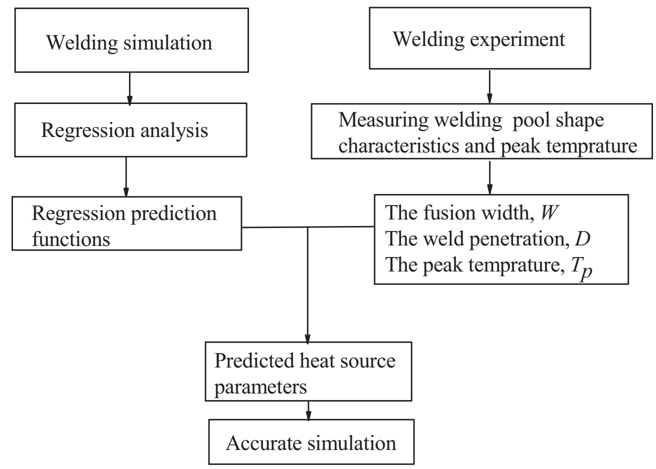

Fig. 2. The basic idea of estimation process.

there still haven't any reports about the application of the PLSRA for parameters estimation in welding process.

In this study, an accurate simulation analysis method in predicting welding heat source parameters was presented. The basic idea of estimation method was showed in Fig. 2. In order to instruct the experimental design, two levels fractional factorial sensitivity analysis was examined [17]. A new attempt using the PLSRA in prediction of welding heat source parameters was made. Moreover, the applicability and accuracy of the PLSRA in welding parameters prediction were discussed. The regression functions were obtained with both the PLSRA and the MRA. The results from these two regression methods were compared. A welding experiment was carried out so as to verify the accuracy of the setting method in this work.

2. Simulation model

The FE (finite element) simulation on circumferential welding pipe was performed in this paper. The rotational symmetry condition (axi-symmetric condition) has been employed in order to reduce computational power requirements. Therefore, a half 2D axi-symmetric pipe weld model with carbon structural steel C22, of which chemical composition and thermal properties were listed in Table 1 and Fig. 3 [18], was developed to study the relationships between welding pool characteristics and heat source parameters. The finite element model and mesh arrangement were presented

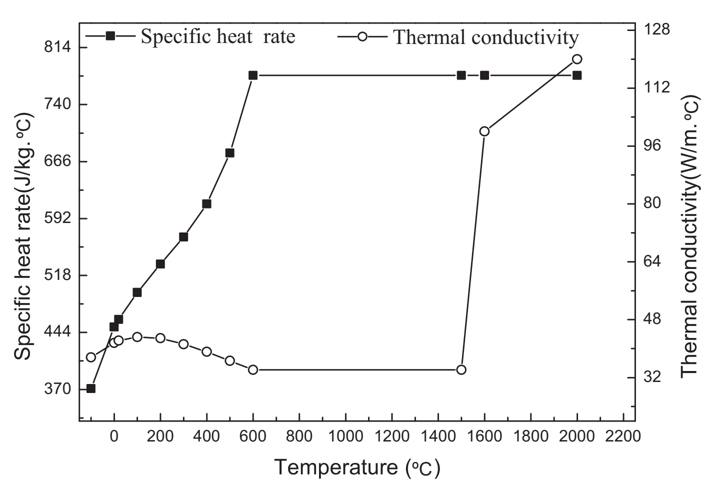

Fig. 3. Thermal properties of C22 [22].