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The Numerical Simulation and Control of Microstructure in Heat-affected Zone in GMAW

Tianqi Wang, Liangyu Li, Xiao Li & Xu Yang

Tianjin Key Laboratory of Advanced Mechatronics Equipment Technology

Tianjin 300160, China

E-mail: wtq0622@163.com

Abstract

The grain size in heat affected zone (HAZ) of welding piece is an important element for evaluating the welding quality. The Monte Carlo (MC) technique, a stochastic simulation method, could be applied to simulate the microstructure in HAZ. A finite element model (FEM) was employed to simulate the GMAW temperature field and the data of the thermal cycle were used to combine with the MC numerically model to calculate the grain size in different welding heat input. Then mathematics model of the grain growth could be worked out by both the kinetic model and the MC model. The dynamic process was simulated by the result of the simulation. The experimental result was used to prove the validity of this method in simulating of microstructure.

Keywords: Finite element model, Monte Carlo model, Microstructure, Grain growth

1. Introduction

The grain size in HAZ is a very important characteristic for evaluating the properties of the welding piece. In welding process the heating and cooling of work piece are un-uniform and the welding parameters play an important role in the control of microstructure, so the research of grain growth during the different heat input are important.

Usually the study of microstructure is made through careful experiment, analysis and comparison. A lot of time and labor will be consumed. Wei et al. established a simulation of grain growth, used the 2-D MC model and the relationship between the MCS and the grain size in ferritic steel are obtained. Dai et al. proposed several improvements for MC simulation, in the program the shortcoming of primitive model could be overcome by these improvements. Shi et al. simulated the Austenite grain growth of the weld joints for the ultra fine grain reinforcement steel bar, in the simulation the heat pinning effect of temperature is considered. Wei et al. used three MC methods to simulate the grain growth in HAZ of stainless steel sus316.

In this study the FEM based on GMAW temperature field and the MC method of microstructure are combined. The two analytical solutions are used to study the relationship between different heat input and microstructure in HAZ. Many experiments are performed to evaluate the availability of the method.

2. FEM model of welding temperature field and MC model of grain growth

2.1 Double- ellipsoidal heat source

For the purpose to calculate the process of grain growth accurately, the thermal cycle obtained from the FEM model must be coincidence with the actual welding.

The double ellipsoidal heat source is chosen to use in the FEM analysis so that the distributive nature of the heat source provided by the electric arc is described more realistically. The heat flux equation is described respectively as:

The first semi-ellipsoidal equation which represents in front of the welding arc is:

$$q_f = \frac{6\sqrt{3}r_f Q}{a_f bc}\exp\left[-3\left(\frac{x-vt}{a_f}\right)^2 - 3\left(\frac{y}{b}\right)^2 - 3\left(\frac{z}{c}\right)^2\right] \tag{1}$$

The second semi-ellipsoidal equation which describes the rear section of the arc is:

$$q_b = \frac{6\sqrt{3}r_b Q}{a_b bc}\exp\left[-3\left(\frac{x-vt}{a_b}\right)^2 - 3\left(\frac{y}{b}\right)^2 - 3\left(\frac{z}{c}\right)^2\right] \tag{2}$$

where af,ab,b,c are shape parameters of double ellipsoidal heat source, Q refers to heat flux, v refers to weld speed, t

refers to the time of welding process, rf and rb refer to proportion coefficient representing heat apportionment in front and back of the heat source respectively, where rf + rb=2.

In the process of GMAW, before the droplet dropped into the molten pool, the enthalpy of droplet could be described below:

$$h_d = \int_{To}^{Tm} c_p(s)dT + \Delta h + \int_{Tm}^{Td} c_p(l)dT \tag{3}$$

The physical properties of Q235 steel are mentioned in the reference, and obtained by the interpolated calculation. In order to study the grain growth, the properties in some special temperature points are paid more attention. The metal property under 9000C is focused on because it is situation of the austenite grain growth. The solitary line temperature and liquid line temperature (1492/15130c) are considered to evaluate the shape and dimension of the weld pool in the simulation.

2.2 The MC model and the improvement program

Weld researchers have engaged the subject of controlling the microstructure in HAZ for a long time. The concept behind the Monte Carlo method in grain growth simulation is both simple and fascinating. There are no other experimental or theoretical inferences, nor mathematical approximations.

By developing a MC microstructure simulation program and adopting the new algorithm according to Dai's article, the efficiency of calculate analysis is improved. The relationship between the grain and the Monte Carlo step (MCS) in simulation could be obtained by regression analysis through many simulations. The equation derived from simulation as below, where the λis the constant of MC model.

$$D = 2.52\lambda(\mathrm{t_{mcs}})^{0.34} \tag{4}$$

2.3 The mathematic model of austenite grain growth and experiment

The chemical composition of Q235 is shown in table.1.The specimen is made by XQ-2 Metallographic Embed machine. Then it is fine polished, buffered and etched with a solution containing picric acid and surfactant. Specimen in the solution is heated until the solution gets boiled. In this method the austenite grain boundary has a priority shown under the microscope. The view field in the Olympus GX51 microscope is magnified 100 to 1000 times to observe the austenite grain, and the grain size is estimated.

According to the study of Sun Junsheng, the material parameters of Q235 are obtained. The material constant is 2.14×1015mm4/min, the activation energy is 54473J/mol, the equation of Q235 is:

$$D^4 - D_0^4 = 2.7\times10^{15}\times0.792\sum_{t=900}^{t'=900}[\exp(\frac{-63900\times0.852}{T(t)})]\Delta t \tag{5}$$

Where D0= 0.02mm, which is the initial size of grain. Substitute the equation 4 into equation 5, and whereλ=5μm, the equation of MSC is established below:

$$t_{mcs} = \left[\frac{(2.14\times10^{15}\sum_{t=900}^{t'=900}[\exp(\frac{-54473}{T(t)})]\Delta t + 0.02^4)^{0.25}}{2.52\times0.005}\right]^{2.94} \tag{6}$$

3. Experiments and verification

3.1 The welding experiment

The equipments used in experiment are Fanuc M100iB (a 6-DOF welding robot) and Lincoln Power Wave F355i (a welding control system). A software Wave Designer provided by Lincoln Electric is used to control the welding parameters in welding process, such as current, voltage, frequency, etc. The welding speed is set up by the teach pendant of the robot. The welding parameters are as shown as follow: the voltage of weld is 20V. The peak current is 200A and the base current is 20A; the frequency of current is 50HZ. The speed of welding is 4mm/s.The wire feed speed is 47mm/s. A shield gas is mixture of 5% co2 and 95% argon.

The work piece is made up of Q235 steel, whose volume is 100mm×40mm×3mm. After the welding completed the work piece is sectioned and polished. Then it will be etched with a solution which contains 97 percent ethanol and 3 percent nitric acid to reveal the weld pool shape. Finally XTL-3400 microscope is used to observe and get the picture of the work piece latitude section.

The latitude cross section derived from the simulation is chosen to compare with the experimental result. The

comparison between calculated and measured is shown in table2.

The thermal cycle curves of different position from fusion line are obtained in the FEM software. A piecewise linear interpolation calculation is employed to calculate the data on the thermal cycle curves. And these data will be used to calculate the grain size.

The data of thermal cycle curve is substituted in the equation 5. Then the grain size in different point will be calculated out. The relationship between temperature field and microstructure in HAZ is established.

The grain size in HAZ is estimated from specimen and grain size of experiment and calculation are compared. The result in fig.3 shows that this method could predict the grain well.

A further operation is to display the simulation picture of microstructures in computer. In Fig.4 the distance from fusion line is 200 to 500μm , and the view field amplified 200 times. The equation 5 is employed to calculate the MSC. And the data of MSC are used to simulate the microstructure. The result of simulation is obtained as Fig.5 shown.

3.2 The relationship between grain size and heat input and grain size

The grain size in the different heat input and different size of work piece could be obtained through the simulation of the FEM and MC method. Fig.6 (a) and (b) show the relationship of the grain size in different heat input. In the different welding power the process of grain growth is shown in fig.6 (a). The more welding power would heat the work piece's temperature higher, and the cooling time would get longer. So that the grain size of corresponding points in the high welding power would larger than low one. As fig.6 (b) shown, the grain growth also could be affected by the different welding velocity. The heating time would be shortening by the quicker welding, and the growth of grain size could be smaller than slowly welding condition. As fig.6 (c) shown, in the same heat input, because the size of work piece is changed, the grain size would also different. In the condition that, following the thickness increased, the corresponding points in work piece would gain the less power, and the grain size would smaller than the points in the thin work piece.

4. Conclusions

(1) The kinetic model of grain growth of Q235 was obtained by the modification of the kinetic formula of low carbon steel.

(2) Based on the thermal cycle of FEM, the Q235 austenite grain growth in HAZ was simulated by MC method. The experiment is used to evaluate the validity of this method.

(3) The relationship between the grain size and the different heat input and different size of work piece was obtained.

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Table 1. Chemical composition of weld material Q235 (%)

C	Si	Mn	S	N	P	Al
0.19	0.21	0.74	0.03	0.85	0.017	0.019

Table 2. Weld value's comparison between calculated and measured

	width W/mm	Penetration h/mm
calculation	1.500	1.104
experiment	1.640	1.117

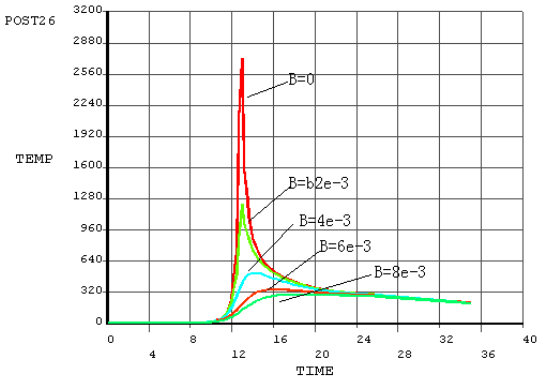


Figure 1. Thermal cycle curves of different position from center of heat source

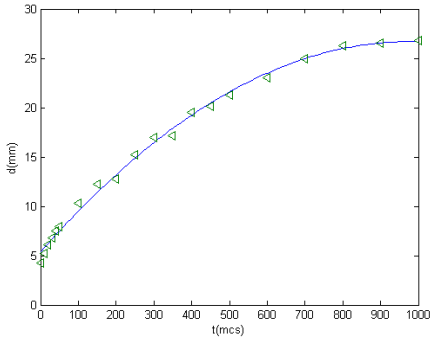


Figure 2. Relationship between MC step and the dimension of grain

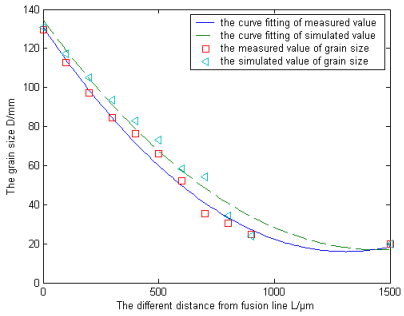


Figure 3. Grain size comparison of experiment and calculation

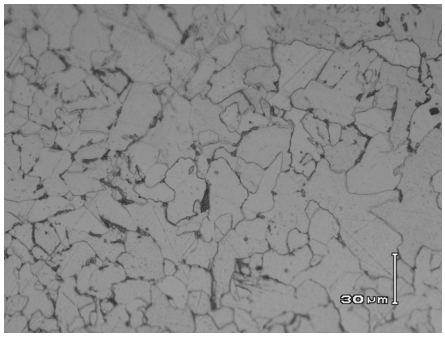
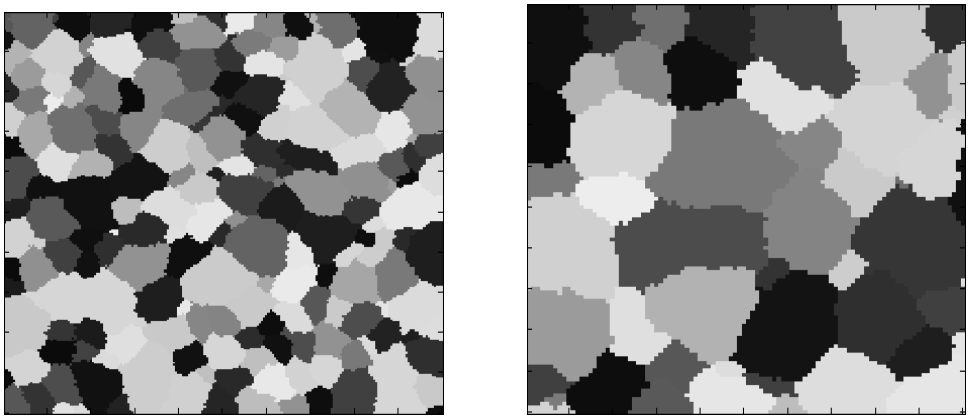
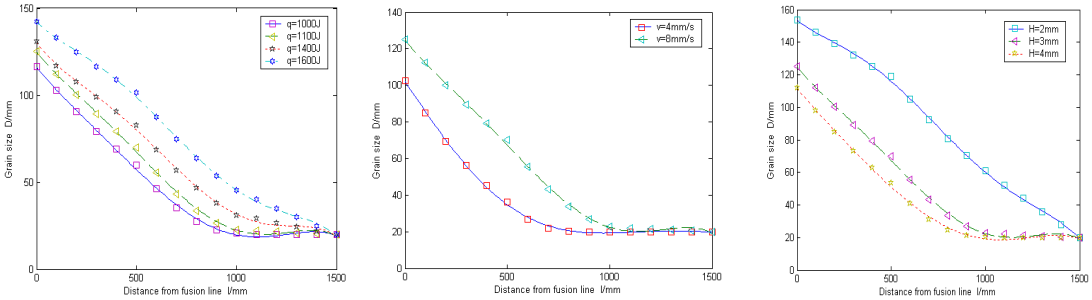


Figure 4. Microstructure of Austenite grains at positions in HAZ of Q235



(a) (b)

Figure 5. The simulation picture of Austenite in different position (a, b indicate the msc=511 d=104.9μm and msc=175 d=73.0μm respectively.)



(a) Effect of different welding power (b) Effect of different welding velocity (c) Effect of different thickness

Figure 6. The compare of austenite size in different condition