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Simulation and control model for interactions among process parameters of directional solidification continuous casting ①

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[Abstract] On the basis of analyzing the principles, equipment and control needs of directional solidification continuous casting (DSCC) process, the building and fulfilling methods of control model of DSCC procedure by neural network control (NNC) method were proposed and discussed. Combining the experimental researches, firstly the computer is used to simulate the effects of those solidification parameters on destination control variable (S/L interface) and the reactions among those parameters during DSCC procedure; secondly many training samples can be obtained. Moreover, after these samples are input into neural network software (NNs) and trained, the control model can be built.

[Key words] directional solidification; continuous casting; control model
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1 INTRODUCTION

It is well known that materials with continuous directional crystals, such as columnar grains, fiberre-inforced composite and single crystal material etc, are used in industry for some especial purposes. However, these materials are difficult to produce. The DSCC process (directional solidification continuous casting process) is a new type of continuous casting technology developing rapidly in recent years. Theoretically, with such a process, unlimited-length and mirror-smooth-surface directional structure metals without internal shrinkage and porosity can be made[1~5]. DSCC process has combined the advantages of DS technology and CC technology, so it is different to traditional casting. As so far, there have been numerous contributions to its theory and design for technical parameters, but few to interaction mechanism among the several parameters and their effective control. In this paper, some basic work about the optimal control methods for solidification parameters of DSCC procedure was carried out.

2 DIRECTIONAL SOLIDIFICATION CONTINUOUS CASTING

The basic idea of DSCC process is shown as Fig.1, which differs from common continuous casting mainly in the mold. In DSCC process, a heated mold, not a traditional water-cooled one, is used, and a separated cooler as a crystallizer is designed. Temperature of the heated mold is higher than that of the molten metal in the bath (i.e, above the melting point of metals), so that free nucleation on the surface of the mold is prevented and unidirectional solidification condition is built. Under proper technique, the surface of the ingot drawn off the exit of the mold will be liquid yet, in other words, a layer of liquid film always exists between the drawn ingot and the mould wall of the mold. This liquid film solidifies freely within a short distance off the exit of the mold, and forms a mirror smooth surface, i.e., the solid/liquid interface locates within a very narrow region off the mold exit. Meanwhile, the friction force between the ingot and the inner wall of the mold is so little that continuous withdrawal of ingot is possible because of the existence of the liquid film.

In the DSCC procedure, the length of the free liquid film off the mold exit, z, would be limited for ensuring the stable growth of directional crystals without break-off of the ingot or leakage of the melt. The surface tension of the melt and the diameter of the ingot determine the length of the free liquid film[4]. This means that the solid/liquid (S/L) surface location is considerably restrictive. Researches have shown that to keep S/L interface location within 1 ~ 2 mm off the mold exit is a prerequisite for formation of stable and continuous directional solidification structure. And the S/L interface shape then becomes a key factor of determining which kind of directional structure to be formed. A S/L interface convex to liquid phase is beneficial to forming single crystal ingots, a flat S/L interface to directional columnar grains or fiber-enhanced in-situ composites, and a concave one to non-normal crystal structure[5~7].

2.1 Thermophysical and mathematical model

From the viewpoint of transmission, the temperature field must be strictly controlled in order to fulfil the directional solidifying continuous casting. The

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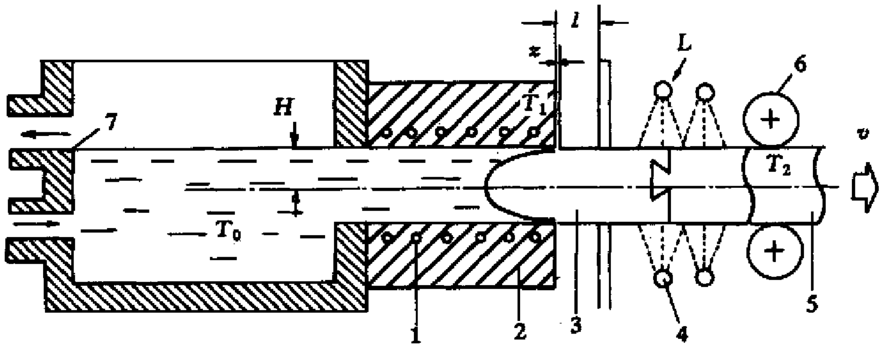

Fig.1 Scheme of DSCC process and its process variables
1 —Heater; 2 — Mold; 3 —Ingot; 4 —Cooling water; 5 —Dummy bar; 6 —Tractive roll; 7 — Molten bath

thermophysical and mathematical model for DSCC can be described by following equations.

Heat-transfer equation:

$$\rho c_P\left(\frac{\partial T}{\partial t}+v\cdot\frac{\partial T}{\partial z}\right)=\frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+q \quad (1)$$

where ρ—density; c_P—specific heat; T—temperature; t—pulling time; v—pulling speed; z—S/L interface location; r—ingot's radius; k—heat conductivity; q—latent heat flux.

Continuity equation:

$$\frac{\partial v_z}{\partial z}+\frac{1}{r}\frac{\partial rv_r}{\partial r}=0 \quad (2)$$

where v_z—the melt's radial flow speed; v_r—the melt's axial flow speed.

Boundary conditions:

1) at boundary of molten bath, $T=T_0$

2) at internal wall of mold, $T=T_1$

3) at cooling water, T_2, L, l.

It is obvious that, S/L interface location z is the location of isothermal surface of temperature T_m, i.e, the molten point of metals. And the temperature field, which is formed by the seven technical parameters through the heat transfer equation and boundary conditions, determines the location of this isothermal surface. These technical parameters are pulling speed v, liquid surface height H, cooling water flux L, cooling distance l, molten temperature T_0, mold temperature T_1, and cooling water temperature T_2.

2.2 Interaction of technical parameters and requirements for control

It has been shown by experiments[3~8] that, the position of S/L interface is determined by the parameters of DSCC among which there exist interactions. For example, parameters T_2, L and l, which decide the cooling intensity of water, not only have an important role on the z, but also affect the parameters such as v and T_1. Put in another way, disturbances of T_2, L and l will cause the disturbances of v and T_1. From the perspective of stable growth of crystal in DSCC process, there is only one goal variable being controlled, i.e, position z of S/L interface, but seven affective factors. Based on the disturbance of z, to control the location of S/L interface means to control these solidification parameters within a range of optimal value and to adjust their values in real time mode. When adjusting these parameters, obviously, both the disturbance of z itself and the interactions of the parameters must be taken into account.

On the cybernetic side, DSCC produce is a dynamic control system with multiple inputs and one output, which belongs to research field of modern control theory. Nevertheless, because DSCC is essentially a complicated multi-factor and non-linear thermo-dynamical system[6], it is very difficult to build a strict mathematical model for it. The design ideas of controller with traditional control methods are all based on an exact mathematical model and on the performance of the control system required by controlled object z[7]. Therefore, it is not feasible to DSCC by means of a traditional control method, and a new one must be considered.

Neuro-control method by which no status vector of the system is required will be more suitable for control requirements of DSCC system, because it could build a model for those complicated non-linear objects which are difficult to be accurately described.

3 DESIGN OF NEURO-CONTROL FOR DSCC SYSTEM

3.1 Modeling with neural net (NN)

Since NN, named artificial neural net (ANN) also, can convert a problem of samples inputted and outputted to that of non-linear optimization via its self-learning and training, so the non-linear mapping between input and output parameters is set up, that is, mathematical model of the object researched is built[9~13].

Fig.2 illustrates the self-learning principle of BP algorithm NN, which is the mature and common used one of NNs. This network is consisted of several layers (no less than two) of nerve cells, and each nerve cell in any layer is connected to each in the adjoining two layers with connect powers between two cells and transfer function. Through repeated sample training to NN, the powers of nerve cells will be modified so that the NN model will gradually approach the real model.

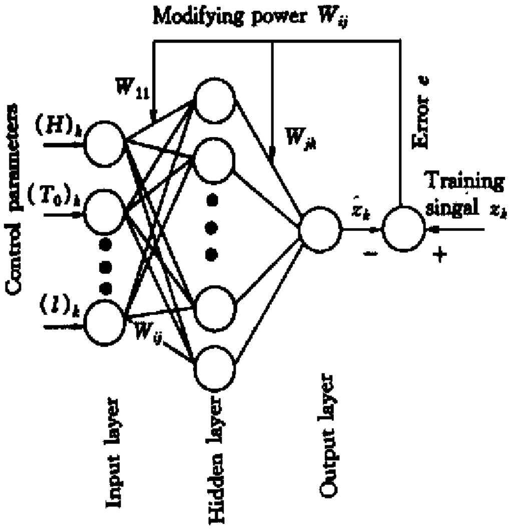

Fig.2 Self-learning of NN model for DSCC procedure

Basic steps of fulfilling modeling with BP algorithm are shown in the following:

1) To initialize, that is, to specify the count of layers of a network being built and the number of cells, and to allocate random arbitrary small values to all nerve cell powers;

2) To supply training sample collection, i.e, input vector $\overline{X}$(that is, H, T_0, T_1, T_2, L, v, and l being unitized) and anticipant output z_d;

3) To calculate real output z_j of arbitrary cell j,

$$z_j = f(\sum W_{ij} x_i) \quad (6)$$

where i is a cell in the previous layer of j, $f(\cdot)$ is the transfer function of this NN, which is generally a function of Sigmoid type,

$$f(x) = \frac{1}{1 + e^{-x}} \quad (7)$$

4) To modify power values in the direction of backward propagation of error, that is, from the output cells to the hidden layer cells and to input layer cells, with the following equation,

$$W_{ij}(t+1) = W_{ij}(t) + \mu \frac{\partial E}{\partial W_{ij}}, \ \mu > 0 \quad (8)$$

where E means the total error of the NN, which is a square type function as following,

$$E = \frac{1}{2} \sum_{k=1}^{N} (z_k - \hat{z}_k) \quad (9)$$

where N is the count of samples;

5) To repeat the step 1) ~ 4) until a satisfactory error is obtained.

Thus an NN model has been built.

In this paper, the model for S/L interface position has 3 layers, with 7 nerve cells in the input layer, 10 nerve cells in the hidden layer and only one nerve cell in the output layer.

3.2 Training samples

The training samples for modeling can be obtained via two ways: experimental measurement and the computer simulation. Although control parameters in the DSCC system such as H, T_0, T_1, T_2, L, v, and l are measurable, the controlled parameter z can be measurable only at a special experimental specimen and it is immeasurable at practical process. Due to the characteristic of this system itself, merely limited samples can be gotten by experimental measurement, however, a lot of samples will be provided through combining experimental measurement with computer simulation. Fig.3 shows a basic simulating flow chart of sample collection for DSCC system.

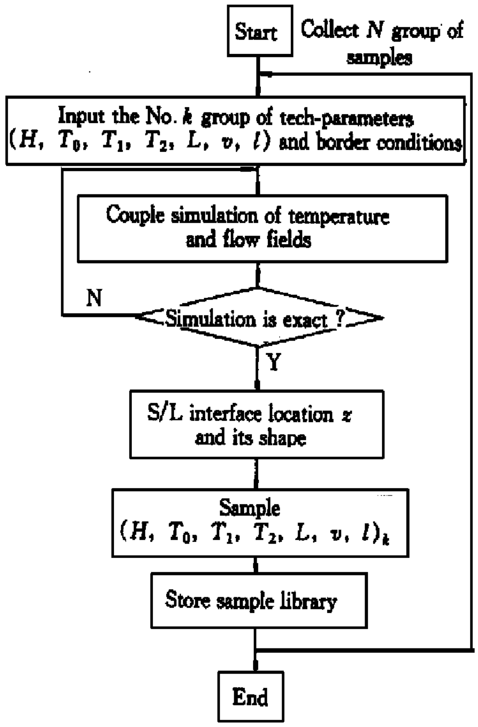

Fig.3 Simulation flow and samples collection of DSCC

3.3 Neuro-control procedure

DSCC is a considerably complex metallurgical procedure, which involves a series of technical steps such as charging, power supply, melting, anti-oxidization, furnace temperature control, cooling, pulling, rolling, parameter measurement, and error alarming. To ensure DSCC system performing for exact and harmonious actions, we selected an industry computer as the control center to manage the system. Fig.4 illustrates the hardware configuration for DSCC system designed by the authors.

In the frame of the present analysis, the basic

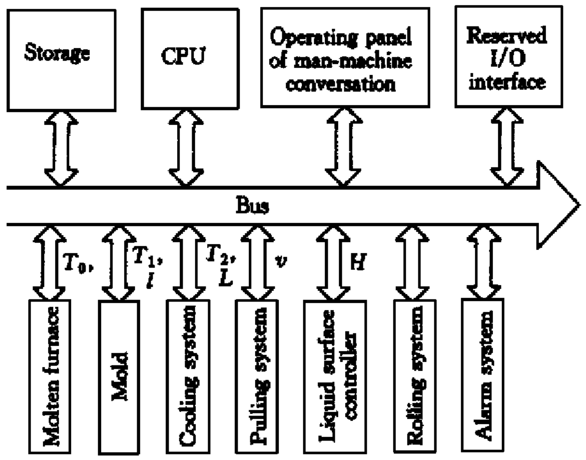

Fig.4 Illustration of hardware configuration of control structure for DSCC system

target of controlling DSCC system is, in fact, to keep the S/L interface location z as close as possible to an anticipant value z_d, which is an constant for a specific material produced. Thus we have an idea that the neural net model trained with samples could be directly used as a controller, instead of traditional PID controller, and the optimal input parameter values are determined through inversion operation by z_d. Because of excellent ability of non-linear approaching of NN, an expected effect of control could be realized. The controller is an inverse model of neural network between the inputs and output. Although theoretically, NN control is suitable for our DSCC system, there are still some limitations existing in NN control method, for instance, the problem of local infinitesimal. So in order to improve the controlling precision for DSCC ulteriorly, combining fussy control to make fussy-neural control will be considered in the future.

4 CONCLUSIONS

1) DSCC system is a complex multi-input-parameter non-linear controlling system and the controlled parameter in the system is subjected to seven technical parameters, which may be affected due to disturbance from the environment and interact each other.

2) It is easy to build a model for the controlled object of DSCC by the neural net method, and the steps of building and realizing the neural control model are illustrated.

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