Modelling and simulation of the electric slag remelting guide vane casting (ESRC) process and its application

To cite this article: Junqing Wang et al 2001 Sci. Technol. Adv. Mater. 2 225

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Modelling and simulation of the electric slag remelting guide vane casting (ESRC) process and its application

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Received 14 June 1999

Abstract

Modelling and experiment work is carried out for a large stainless steel casting with variable cross-section and a curved surface which is produced by the electric slag remelting casting process. The casting is part of a hydraulic runner generator at a power station of a big river. Mathematical models of the heat transfer and melted rate from an expendable metallic electrode were established. The melted rate is related to some important parameters, such as electric current and voltage, temperature and the flow rate of the cooling water in a crystallizer. Electrode melting, the moving pattern of the melted pool and the slag pool and the melt solidification in the metal pool were simulated.

In order to make the enmeshment of the variable curved surface of the casting, a co-operation method of extended constructive solid geometry (CSG) from 9 to 21 uniform geometry with B-Spline surface functions is developed. By this method the guide vane casting is enmeshed. The boundary condition between the steel casting and the crystallizer cooled by water was measured.

Based on the above new content the solidification simulation software ESRC3D is developed. Using it to simulate the whole process of ESRC with different parameters, instead of exploring the technological parameters of casting production by the trial-and-error method, the optimized parameters from the simulation for production of the large stainless steel castings with variable cross-section and a curved surface, such as the guide vane castings, have been used to produce them. Economic benefit and good quality of castings are obtained. Guide vane castings are widely applied to the hydraulic runner generator at numerous river power stations. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Stainless steel casting; Electric slag remelting casting process; Yangzi river

1. Introduction

There is a large amount of sand (∼10 kg/m³) in the Yangzi river, and the speed of water stream is very large. Thus higher tensile properties and better wearing resistance against sand are required for large stainless steel castings with a variable cross-section and a curved surface of a hydraulic runner generator at the power station of the river. If the castings are produced by a sand mould in the foundry shop, not only the defects of shrinkage, porosity, inclusion and cracking often occur in the castings, but also the shape and size of the casting are unstable and its wearing resistance is low. The electric slag remelting casting (ESRC) process has been developed based on the electric slag remelting process of ingots. During the ESRC process, the steel melt is refined and shaped into a casting. All the defects mentioned above are eliminated in the casting. At the same time it has high density, uniform chemical composition and higher mechanical properties, which latter are the same as those of the forging and rolling of steel and near net shape forming. Because of those advantages for castings, they are widely applied in big power stations in rivers.

Until now the technological parameters of the ESRC process have been mainly determined by the trial-and-error method and some empirical formulae that are used for the electric slag remelting of ingots. For large castings the cost of materials and crystallizer is very high. Correcting unsuitable parameters needs many experiments, long time and high cost. It results in obtaining little information of the heat balance, and therefore it is necessary to model and simulate the electric slag remelting process for a large steel casting with a variable cross-section and a curved surface in order to understand the heat transfer rule and to obtain efficient technological parameters.

From 1960 to 1980 modelling and simulation of temperature fields had been carried out during the solidification process of steel castings using a mould. In 1988 the calculation of 3-D temperature fields was achieved by researchers of many countries [1–3]. In the early 1980s many researchers started to simulate the velocity fields of metallic liquid
during the mould filling process, and 3-D velocity-fields calculation for mould filling was also achieved by some advanced researchers in the world in 1995 [4–6]. From 1990 until now a new task is to model and simulate the microstructure and morphology of crystal grains, the trend of simulation being developed from macroscopic problems to microscopic problems [7,8].

In recent years a number of researchers have tried to predict the shape of the melted pool and the height of the mushy zone during the electric slag remelting ingot process by computer simulation, and furthermore to control the solidification process. Choudhary and Szekely proposed a mathematical model of heat transfer [9]; Yu and Adaszcik considered a model with continuously changing solidification area [10]; for both of the models, the moving boundary condition was not taken into account, so that their application is limited. Paton established a mathematical model of transient heat transfer and calculated the shape change of the melted pool from the initial to the stable stage [11]. Jeanfics calculated the temperature distribution in an ingot of a two- elements alloy and the changing of the melting rate [12]. Medovar and Demchenko established a 3-D mathematical model for an electric slag remelting plate plank and calculated the temperature fields [13]. However modelling and simulation of the electric slag remelting casting process, especially of the casing formed in a crystallizer with complicated cavity, has not been reported either nationally or abroad until today.

2. Experiment

An experiment of the electric slag remelting casting process is carried out as shown in Fig. 1. Top and bottom crystallizers are installed together, through which cooling water at room temperature transfers heat from the melted pool at the cavity of crystallizer, whilst a voltage is applied across the expendable metallic electrode and crystallizer. After the electrode strikes an arc with the bottom crystallizer by solid burning agent, all of the slag powder is put into the cavity and melted to form a slag pool above the bottom crystallizer. When the slag temperature is higher than the melting temperature of the electrode, melted metallic material drop falls down to form the melted pool. The liquid metal in the melted pool is solidified into a casting with the same shape as that of the cavity of the crystallizer. The whole remelting and casting process progress continuously form the bottom to the top, and do not stop until the casting is fully filled inside the crystallizer.

3. Calculations

When conducting numerical simulation, it is necessary to input date related to the shape of the casting, making up a data file to construct solid geometry, then to enmesh it and to calculate the heat transfer between the variable meshes. A co-operation method of extended constructive solid geometry (CSG) from 9 to 21 uniform geometries with B-Spline surface functions is developed. By this method the guide vane casting is enmeshed as shown in Fig. 2. The casting is divided into three parts, the upper long shaft, the middle clack and the lower short shaft.

Heat conducts between the melted pool and the slag pool, liquid metal solidifies in the melted pool, and both heat of
conduction and convection occur between the solidified metal and the crystallizer. In these cases the energy equation is adopted as the model of heat transfer, which is shown in Eq. (1):

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} = a \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{L}{C_p \rho}$$ (1)

During the ESRC process, the melted rate of metallic material dropping from the electrode is related to the voltage applied, the current value, the heat transfer from the slag pool to air and from the melted pool to the crystallizer, heat absorption by the slag, electrode and liquid metal, the flow rate of the cooling water, the temperature of the water and so on. Therefore a model should be found to describe all of those phenomena. According to the physical analysis, Eqs. (2)–(5) could be adopted to calculate the melted rate of the metallic dropping from the electrode.

Supposing: $Q$ is the input total quantity of heat; and $Q'$ is the output total quantity of heat from the slag pool: then $Q_s, Q_a,$ and $Q_e$ are the quantity of heat for preheating, melting and superheating of the electrode. For one time step:

$$Q = IV \Delta t$$ (2)

$$Q' = Q'_1 + Q'_2 + Q'_3 + Q'_4$$ (refer to Fig. 3) (3)

$$Q_s = Q - (Q'_1 + Q'_2 + Q'_3 + Q_e1 + Q_e3)$$ (4)

$$G = \frac{Q_c}{L}$$ (5)

where $I$ is the input current (A); $V$ is the input voltage (V); $\Delta t$ is the time step (s); $Q'_1$ is the quantity of heat conducted from the crystallizer ($Q'_2$ is the heat convected from the surface of the electrode ($Q'_3$ is the radiated quantity of heat from the top surface of slag pool ($Q'_4$ is the conducted quantity of heat from the slag pool to the melted pool ($L$ is the latent heat of steel (J/kg); and $G$ is the melting rate of the metallic electrode (kg/s).

The boundary condition between the casting and the crystallizer was measured by a thermocouple in the production of a guide vane casting for the Taipingyi power station. The measured temperature at point one (7 mm from the surface of the casting and 550 mm from the bottom) is shown in Fig. 5 and at point two (22 mm from the surface of the casting and 550 mm from the bottom) is shown in Fig. 6. The temperatures of the cooling water flowed into the crystallizer is shown in Fig. 4: the temperature of the water flowed out of the crystallizer is 2–3°C higher than that flowing into it (Figs. 5 and 6).

Based on the above method of constructing the solid geometry, mathematical models, boundary condition, and
the continuously changing calculated area and varied category of the mesh, ESRC3D software was developed. The whole electric slag remelting casting process in the production of guide vane castings was simulated for the Lam Takho power station, which is located in Thailand, as shown in Figs. 7–10.

1. Construction of solid geometry of the castings and enmeshing them can be done by ESRC3D software.
2. Electrode melting, and slag and melted-pools forming, can be simulated.
3. The slag and Melted pools rising, electrode melting and shortening, casting forming, namely, the whole ESRC process with certain technological parameters, can be simulated.
4. Temperature fields can be simulated at any part of the casting and at any time during the ESRC process.

| Material       | Method    | Inclusion % | Metallograph grade |
|----------------|-----------|-------------|--------------------|
| Ocr13Ni5Mo    | Sand mould| 0.0090–0.0140| 2.5–3.5            |
|                | ESRC      | 0.0034–0.0040| 1–1.5              |
Table 2
Comparison of compositions

| Material       | Casting        | C    | Si   | Mn   | S    | P    | Cr   | Ni   | Mo  |
|---------------|----------------|------|------|------|------|------|------|------|-----|
| Cr13Ni5Mo    | Sand mould     | 0.045| 0.56 | 0.55 | 0.032| 0.02 | 13.70| 4.60 | 0.68|
|               | ESRC           | 0.04 | 0.55 | 0.53 | 0.015| 0.016| 13.53| 4.60 | 0.65|

Table 3
Comparison of mechanical properties

| Material       | Heat           | Method       | Mechanical properties |
|---------------|----------------|--------------|-----------------------|
| Cr13Ni5Mo    | 1000°C + 600°C | sand mould   | YS (N/mm²) | UTS (N/mm²) | EL (%) | RA (%) | Aₜ (J/cm²) | HB  |
|               |                | ESRC         | 675    | 830    | 17     | 50     | 70         | 260 |
|               |                |              | 695    | 835    | 20     | 66     | 109        | 262 |

5. Application of ESRC process

The ESRC process with different technological parameters could be simulated by ESRC3D software. The authors have analyzed: the time needed; if the temperature gradient is reasonable; if defects of shrinkage, porosity, cracking and inclusions occurred or not; and so on; further optimized technological parameters, and then used them to instruct the practice of casting production. The castings of the guide vane, blade and spray needle head for a hydraulic runner generator; and a valve body for natural gas have been produced in recent years, these castings being applied in power stations of Yangzi and Yellow rivers in China. From 1984 to 1998, 998 guide vane castings of 1578 ton mass were applied in 15 power stations. The comparison between castings produced by sand moulding and the ESRC process in terms of inclusion quantity, composition, mechanical properties and erosion resistance, are shown in Tables 1–4, respectively. To sum up these results, all of the properties of castings produced by the ESRC process are much better than that by sand moulding.

Large stainless steel castings with variable cross-section and a curved surface, such as guide vane castings, have been produced using these optimized parameters. Economic benefit and good quality of castings are obtained by saving the cost of electric power and material loss, improving, the design of the expendable metallic electrode and crystallizer and shortening the production time. At the same time, a new type of steel casting by the ESRC process is presented for engineering practice in the future.

6. Conclusions

1. Suitable mathematical equations were established for the melting rate of the electrode, forming the melted pool and simulating the solidification process of casting.
2. A co-operation method extended from 9 to 21 uniform geometry with B-Spline surface functions is developed to construct the solid geometry of the castings and to enmesh them.
3. ESRC3D software is able to simulate the whole ESRC process, including: electrode melting, both of the melted pool and the slag pool; forming and moving; melt solidifying into the casting; showing the temperatures fields at any position and at any time; and to optimize the technological parameters of the ESRC process.
4. Stainless steel castings with variable cross-section and of curved surface, such as guide vane castings can be produced by using optimized technological parameters. Their mechanical properties are better than those of castings made by using a sand mould.

Acknowledgements

This research work was funded by both the National Natural Scientific Foundation China and the Technical Development Foundation Commission of the Ministry of Machinery Industry. Dr Xun Sun and Mr Baozhi Li who gave much help are greatfully acknowledged.
References

[1] R.E. Moroen, J.O. Wilkes, R.D. Pehlke, Numerical simulation of solidification, Part I and II, Cast Metal Res. J., USA 6 (1970) 184–192.
[2] E. Niyama, T. Uchida, M. Morikawa, S. Saito, Predicting shrinkage in large steel castings from temperature gradient calculation, AFS Int. Cast Metals J. 6 (1981) 16–22.
[3] Yi Zhang, Junqing Wang, Enchang Yang, Numerical simulation of solidification process of castings, J. Foundry, China 1 (1980) 10–16.
[4] R.A. Stoehr, Simulation in the design of sand casting, Proceedings of Modelling Casting and Welding Process, Ringe, New Hampshire, USA, 1980, pp. 13–18.
[5] R.A. Stoehr, C. Wang, W.S. Hwang, P. Ingerslev, Modelling the filling of complex foundry mould, Proceedings of Modelling Casting and Welding Process III, Santa Barbara California, USA, 1986, pp. 303–313.
[6] Junqing Wang, S.F. Hansen, P.N. Hansen, 3-D modelling and simulation of mould filling using PC’s. Proceedings of Modelling Casting and Welding Process VI, Palm Coast, Florida, USA, 1988, pp. 741–753.
[7] P. Zhu, R.W. Smith, Dynamic simulation of crystal growth by Monte Carlo Method-I model description and kinetics, Acta Metall., Mater. 40 (4) (1992) 683–692.
[8] Dianzhong Li, Shifang Su, Xuehua Xu, Junqing Wang, Modelling of microstructure formation for nickel based super alloy turbine blade casting, Proceedings of 61st World Foundry Congress, Beijing, China, 1995, pp. 63–74.
[9] M. Choudhary, J. Szekely, Metall. Trans. 11B (1980) 439–452.
[10] K.O. Yu, C.B. Adasczik, Proceedings of 7th International Symposium on ESR and other Special Techniques II.
[11] B.E. Paton, B.I. Medover, Electroslag Refining, London, 1973, p. 16.
[12] C.I. Jeanfics, J.H. Chen, Proceedings of 6th International Conference on Vac. Met., 23–27 April 1979.
[13] B.I. Medovar, V.F. Demchenko, Proceedings of 5th International Conference on Vac. Met. and ESR Proc. 11–15 October 1976.