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Numerical simulation of semisolid continuous casting process①

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[Abstract] A general mathematical model and boundary condition applicable to momentum and heat transfer in the semisolid continuous casting(SCC) process was established. Using the model, the numerical simulation of the momentum and heat transfer of molten metal was carried out in the SCC system. The obtained results fit well with the measured ones. Moreover, using the numerical simulating software, the effect of various factors on breakout and breakage was explored. The obtained results show that heat flow density of copper mold and the withdrawal beginning time are two major influencing factors. The larger the heat flow density of copper mold, or the shorter the withdrawal beginning time, the more stable the semisolid continuous casting process.

[Key words] semisolid continuous casting; numerical simulation; mathematical model

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1 INTRODUCTION

Semisolid continuous casting(SCC) is still in the experimental study stage in China[1~3]. Therefore, many problems are needed to be explored continuously. Among them, the breakage and breakout are the key blocks to limit the industrial application of the process. Because of the complexity in mechanisms and the difficulty in experimental research, the study on the process advances slowly. However, the numerical simulation, an important method for research, has made great progress. It may offer the study of the SCC process with a new means[4~6]. In fact, by using numerical simulation, the momentum and heat transfer can be calculated simultaneously, and the possibility of the breakage and breakout may be predicted. Moreover, the effects of various factors on the stability of the SCC process can be studied quantitatively. So, the application of the numerical simulation in the research of the SCC process is very important.

2 MATHEMATICAL EQUATION AND BOUNDARY CONDITION

2.1 Mathematical equations

Because of magnetic stirring, the flow of the semisolid melt in the SCC system appears very complicated. However, it still can be looked on as unsteady flow of the viscid and incompressible fluid on the condition that the viscosity is settled properly[5]. Moreover, because the semisolid slurry has good fluidity[7], the flow of it can also be regarded as lamellar one. Therefore, the SCC process can be mathematically described by an improved magnetic fluid equation. In order to solve the equation, the heat transfer equation must be considered simultaneously. So, the complete mathematical equations include the following three parts.

1) Equation of Mass Conservation:

$$\frac{\partial \rho}{\partial t}+\frac{\rho v_r}{r}+\frac{\partial(\rho v_r)}{\partial r}+\frac{\partial(\rho v_z)}{\partial z}=0 \qquad (1)$$

2) Equation of Momentum Conservation

$$\left.\begin{aligned}
&\frac{\partial(\rho v_r)}{\partial t}+\rho v_r\frac{\partial v_r}{\partial r}+\rho v_z\frac{\partial v_r}{\partial z}-\frac{\rho v_\theta^2}{r}= \\
&\qquad -\frac{\partial p}{\partial r}+F_r+\mu\Big(\frac{1}{r}\frac{\partial v_r}{\partial r}+\frac{\partial^2 v_r}{\partial r^2}- \\
&\qquad \frac{v_r^2}{r^2}+\frac{\partial^2 v_r}{\partial z^2}\Big) \\
&\frac{\partial(\rho v_\theta)}{\partial t}+\rho v_r\frac{\partial v_\theta}{\partial r}+\rho v_z\frac{\partial v_\theta}{\partial z}+\frac{\rho v_\theta v_r}{r}= \\
&\qquad F_\theta+\mu\Big(\frac{1}{r}\frac{\partial v_\theta}{\partial r}+\frac{\partial^2 v_\theta}{\partial r^2}-\frac{v_\theta}{r^2}+\frac{\partial^2 v_\theta}{\partial z^2}\Big) \\
&\frac{\partial(\rho v_z)}{\partial t}+\rho v_r\frac{\partial v_z}{\partial r}+\rho v_z\frac{\partial v_z}{\partial z}-\frac{\rho v_z^2}{r}= \\
&\qquad -\frac{\partial p}{\partial z}+\rho g+\mu\Big(\frac{1}{r}\frac{\partial v_z}{\partial r}+\frac{\partial^2 v_z}{\partial r^2}+\frac{\partial^2 v_z}{\partial z^2}\Big)
\end{aligned}\right\} \qquad (2)$$

3) Heat Transferring Equation:

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$$\rho(c_p + \frac{L}{T_L - T_S})\frac{\partial T}{\partial t} + c_p\rho v_r \frac{\partial T}{\partial r} + c_p\rho v_z \frac{\partial T}{\partial z} = k(\frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2}) \quad (3)$$

where the viscosity coefficient μ is a function of the fluid velocity and solid fraction[6, 8], and can be expressed as

$$\mu = \frac{1}{2} a e^{b\varphi_s}(\frac{v_\theta}{r} + \frac{\partial v_\theta}{\partial r} + \frac{\partial v_\theta}{\partial z})^{\alpha} \quad (4)$$

In Eqns. (1) ~ (4), v_r, v_θ, v_z —the fluid velocity component on the r, θ, z directions respectively, m/s; F_r, F_θ —the magnetic force component on the r, θ directions respectively, N; T_L —the liquidus of alloy, K; T_S —the solidus of alloy, K; p — the pressure, N; T —the temperature, K; ρ—the density of the semisolid melt, kg/m^3; c_p —the specific heat of the semisolid melt, J/(kg·K); k —the thermal conductivity of the semisolid melt, J/(m·K); g —the acceleration of gravity, m/s^2; L —the crystallize latent heat, J/mol; φ_s —solid fraction of the semisolid slurry; a, b, α —the constants to be determined experimentally.

2.2 Initial and boundary conditions

2.2.1 Initial condition

When $t = 0$, $T = T_p$, $v = 0$, $\varphi_s = 0$, $\Delta p = 0$

2.2.2 Boundary condition

1) Boundary condition for temperature field

At axis line: $\frac{\partial T}{\partial r} = 0$;

At melt surface in stirring chamber: $T = T_p$;

At the lower boundary of mold: $\frac{\partial T}{\partial z} = 0$;

At the interface between the stirring chamber and mold: $-k\frac{dT}{dr} = q$

2) Boundary condition for fluid field

On all of the boundary, such as the axis line, melt surface in the stirring chamber, the lower boundary of the mold, the stirring chamber and mold, the velocity equals to zero($v = 0$).

By using the method of crisscross net check[9] and explicit finite deference scheme[9, 10], Eqns. (1) ~ (4) are solved, and the velocity and temperature field are obtained.

3 RESULTS AND DISCUSSION

The experiment is carried out on the SCC machine made in China. By using PtRh-Pt thermocouple with the diameter of 0.5 mm and an auto-balance record meter, the temperature of the semisolid slurry of 0.2% carbon steel is measured and recorded continuously. The numerical simulation results and the test results are shown in Fig. 1. It can be seen that the results obtained by the numerical simulation is the same as the test results basically. It is very interesting that there is a point of intersection at 145s in Fig. 1. Before this point, the measured temperature is higher than the numerically simulated one. But after it the former is lower than the later. The phenomenon can be explained by the different condition in the test and numerical simulation. In the test, the stirring chamber is filled and never poured again afterward, but in the numerical simulation the liquid in it is assumed in a constant level. However, from the fact that the test results and numerical simulation results are fitted well in the initial stage, thus a conclusion can be drawn that the general mathematical model is reasonable and reliable.

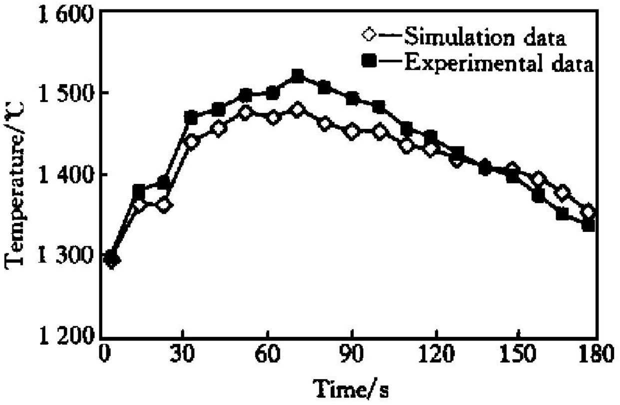

Fig. 1 Comparison of temperature field calculated and measured

4 STABILITY OF SCC PROCESS

The SCC test shows that the breakage and breakout are two typical unsteady phenomenon of the process. Their mechanisms are assumed related with the friction between the billet and the mold. Because there is no any vibrating equipment, large friction between the billet and the mold is found. When the withdrawal begins, it is sure to form a crack at some position because of the friction. The higher the crack location, the easier the welding and the better the stability of the SCC process[11]. Consequently the stability can be predicted according to the position of the initial crack. And the Eqn. (5) is the decision basis on the initial location of the crack. On the other hand, the thickness of the solidified shell at the crack position has a complicated effect on the stability of the SCC process and can be acted as another parameter to predict the stability of the process.

$$Z = \frac{1}{2}\left\{\frac{d}{\sqrt{2y - c}} - c - \sqrt{2y - c}\cdot\sqrt{\frac{2d}{\sqrt{2y - c}} - 2y - c}\right\} \quad (5)$$

where Z is the location of the initial crack, mm; c, d, y are the functions of the friction coefficient, solidification coefficient, grade of the temperature and withdrawal rate.

On the basis of the former software, new software called "SSM-Ⅱ" is constructed, which can be used to explore the stability of the process. Using this software, the effect of major factors is first studied by computer, and then the successful design for the process can be obtained.

The previous tests show that the main factors which affect the temperature distribution of the semisolid melt are the withdrawal beginning time, pouring temperature, heat flow density, copper mold length and withdrawal rate[10]. In order to determine the effect of those factors on the SCC process and get the best design for the process, a series of experiments for the above 5 factors each with 5 levels is designed and carried out by the software "SSM-II". The control factors and their levels used in the simulation experiment are list in Table 1.

By statistical analysis to the data of the simulation experiments, the extreme difference values which show the effect of every factor on the location and solidification shell of the initial crack are obtained and list in Table 2 and Table 3. The bigger the extreme difference value, the larger the effect of the factor. From Table 2 and Table 3, it can be seen that heat flow density of copper mold is the most significant influencing factor on the stability of the process, while withdrawal beginning time take the second place. Choosing the level of every factor that corresponds to the small value of the crack height in Table 2, and a better project of the process *A*1-*B*4-*C*1-*D*1-*E*5 is got. But choosing the level of every factor that corresponds to the big value of the thickness on the crack place in Table 3, and another better project *A*5-*B*1-*C*5-*D*1-*E*1 can be gotten. Synthetically considering the stability of the SCC process and the simulated results, it can be seen that the actual best project is *A*3-*B*2-*C*3-*D*1-*E*4. Namely, the withdrawal beginning time is 30 s, the heat flow density of copper mold is 2.2×10^6 W/m^2; the pouring temperature is 1 597 ℃; the copper mold length is 150 mm and the withdrawal rate is 400 mm/min. Based on this project, the simulation test and the actual test are carried out separately. The obtained results (as list in Table 4) are fitted well. The location of the initial crack is 2.1~3.75 mm away from the surface of the mold, and the solidification shell thickness of the initial crack is 1.5~2.0 mm.

5 CONCLUSIONS

1) Considered the characteristic of non-Newton fluid of metal melt and taken the viscosity as a function of the solid fraction and stirring rate, a general mathematical model and boundary condition applicable to momentum and heat transfer in the semisolid continuous casting process is established, and the software to describe the SCC temperature and fluid field is constructed. Using the model, the numerical simulation of the momentum and heat transfer of molten metal is carried out in the SCC system by means of the special software "SSM-Ⅰ".

2) On the basis of the former software, another software called "SSM-Ⅱ" is achieved, which can be used to predict the stability of the SCC process. Using the software "SSM-Ⅱ", the effect of every factor

Table 1 Control factors and their levels

Factor	Withdrawal beginning time (*A*)/s	Pouring temperature (*B*)/℃	Heat flow density (*C*)/(W·m^{-2})	Copper mold length (*D*)/mm	Withdrawal rate (*E*)/(mm·min^{-1})
Level 1	10	1 580	4.0×10^5	150	100
Level 2	20	1 597	1.3×10^6	250	200
Level 3	30	1 615	2.2×10^6	300	300
Level 4	40	1 632	3.1×10^6	400	400
Level 5	50	1 650	4.0×10^6	500	500

Table 2 Effect of various factors on height of initial crack (mm)

Level	*A*	*B*	*C*	*D*	*E*
1	3.852 156	19.561 95	0.209 264	5.750 498	24.843 56
2	12.319 42	14.106 13	3.464 277	8.132 643	15.647 91
3	7.387 831	11.443 95	7.896 269	22.450 90	17.287 85
4	16.150 28	8.662 465	21.995 03	10.079 79	4.845 653
5	27.684 93	13.620 31	33.829 78	12.980 79	4.769 638
Extreme difference	23.832 77	10.899 48	33.620 51	14.318 26	20.073 93

Table 3 Effect of various factors on thickness of initial solidified shell (m)

Level	*A*	*B*	*C*	*D*	*E*
1	0.012	0.020	0.009	0.019	0.019
2	0.015	0.017	0.015	0.018	0.017
3	0.018	0.017	0.018	0.018	0.018
4	0.019	0.015	0.021	0.017	0.017
5	0.023	0.018	0.024	0.016	0.016
Extreme difference	0.011	0.005	0.015	0.003	0.003

Table 4 Comparison between calculated and measured results

	Crack height /mm	Thickness of solidified shell /m
Calculated	2.10	0.0015
Measured	3.75	0.0020

is studied by computer. The obtained results show that the heat flow density of copper mold and the withdrawal beginning time are two major influencing factors. The larger the heat flow density of copper mold, or the shorter the withdrawal beginning time, the more stable the semisolid continuous casting process.

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