MODELING ON MOLTEN METAL'S PRESSURE IN AN INNOVATIVE PRESS CASTING PROCESS USING GREENSAND MOLDING AND SWITCHING CONTROL OF PRESS VELOCITY

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Keywords: Press casting, Pressure control, Computational fluid dynamics, Modeling, Casting detect.

Abstract: This paper presents modeling and control of fluid pressure inside a mold in a press casting process using greensand molding as an innovative casting method. The defect-free manufactures of casting product in the press process are very important problem. Then, it is made clear that the press velocity control achieves to reduce the rapid increase of fluid pressure. A mathematical model of the molten metal's pressure in a casting mold is built by using a simplified mold and investigated the availability by comparison with the CFD model. A pattern of the press velocity from the high speed to the lower speed is derived by using the mathematical model. Finally, the effectiveness of the proposed switching velocity control has been demonstrated through CFD computer simulations.

1 INTRODUCTION

Recently, an innovative method called the press casting process using the greensand mold has been actively developed for improving the productivity by authors group. The casting process is shown in Figure 1. In the casting process, the molten metal is poured

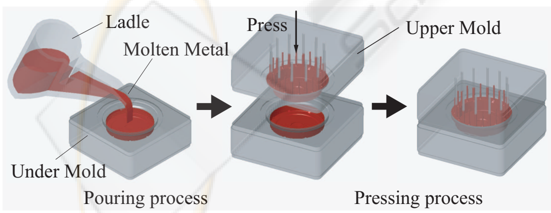

Figure 1: Press casting process.

into the under mold by tilting the ladle. After pouring, the upper mold is fallen down towards the lower mold, and pressed. The process enables us to enhance the production yield rate from 70[%] to over 95[%], since sprue runner and cup are not required in the casting plan(Y.Noda et al., 2006). This process is comprised of two parts such as a pouring and a pressing processes. In the pouring part of the casting process, it is needed to pour the molten metal into the under mold precisely and quickly, and suppress the splash of the molten metal in the mold. In the conventional pouring method, the outflow quantity from the ladle is larger than the volume required in the actual product, and the production yield rate is then decreased. Pouring controls on the pouring process in the press casting were studied by past studies(Y.Matsuo et al., 2006), (Y.Noda et al., 2006).

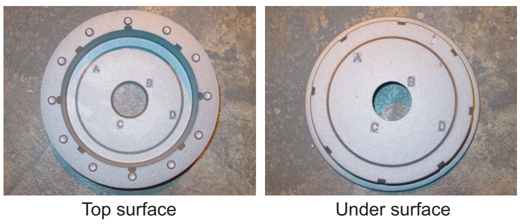

Figure 2: Casting product by an innovative press casting using greensand mold.

On the other hand, in the press part, the casting

Tasaki R., Noda Y., Terashima K., Hashimoto K. and Suzuk Y. (2007).
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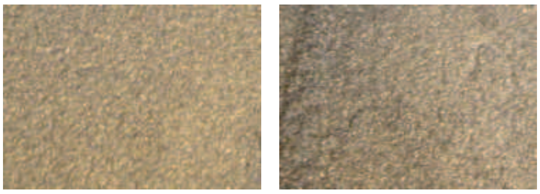
In *Proceedings of the Fourth International Conference on Informatics in Control, Automation and Robotics*, pages 498-503
DOI: 10.5220/0001651704980503



Sound case: v=5[mm/s] Defect case: v=122[mm/s]

Figure 3: Inner surface of products.

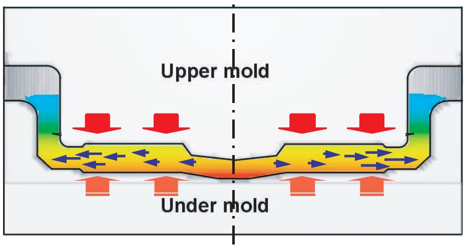


Figure 4: Illustrative figure on fluid behavior of molten metal.

defects are caused by the pattern of press velocity. As an representative example of casting product with a press casting process, a brake drum is shown in Figure 2, where the press velocity is 5[mm/s]. Figure 3 shows the photographs of surface of iron casting produced by Figure 2. In the high speed press such as the velocity of v=122[mm/s], a casting product generates rough surface. This surface defect is called a metal penetration such that the solidified molten metal is soaked among the sand particles in the greensand mold. As seen from Figure 4, this defect is thought to be the generation of high pressure of fluid in the mold due to the rapid velocity of press. Whereas, in the case of slow velocity in the press, a defect of the oxide film in the surface of products and a defect of void due to the rapid solidifications are generated. Therefore, the press velocity control is demanded to adequately suppress the fluid pressure in the high speed press.

The pressure control methods have been proposed in the conventional casting method. To realize the high quality product such as spheroidizing and densification for iron casting, optimal design of sink head is achieved by using the simulation analysis on understanding the explicit solidification property(Louvo et al., 1990). To simulate the filling behavior of molten metal, the rheological characterization has been experimentally studied by H. Devaux(H.Devaux, 1986). 3D-visualization technology was developed by C. Galaup et al.(C.Galaup and H.Luehr, 1986), (I.Ohnaka, 2004). In the injection molding process, the pressure control problem has been successfully achieved by Hu J, 1994. A model on PID gain's selection is proposed for the pressure control in filling process. Then, the effectiveness of a mathematical model with the identified the physical parameters for control performance is verified experimentally(Hu, 1994).

The first keynote on the press casting process using greensand molding has been published by Terashima(K.Terashima, 2006). The press casting process is that the molten metal poured in the under mold is fluidized by the falling down of the upper mold(K.Terashima, 2006). The pressure control by changing the press velocity has not yet been applied, although its importance has been addressed by Terashima in the press casting method. Therefore, we propose to suppress the pressure adequately by controlling the press velocity in the press casting system. The pressure of molten metal in the mold must be detected to control the process adequately. However, measurement of the fluid pressure is difficult, and the use of the contact pressure sensor can not be applied, because the fluid temperature is very high around about 1400. Then, in this paper, the pressure is estimated by using the reaction force measured by a load-cell which is set above the upper mold. A mathematical model of the molten metal pressure in a casting mold is newly given. Based on this mathematical model, an ideal pattern of press velocity is proposed to fall down the upper mold rapidly towards the lower mold with suppressing the fluid pressure.

2 PRESS PROCESS IN PRESS CASTING SYSTEM

The panoramic photograph of the press casting ma-

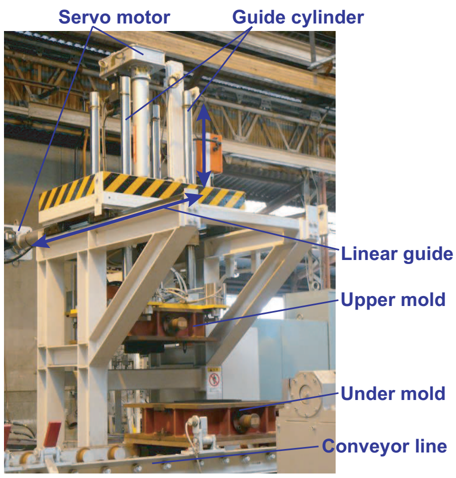


Figure 5: Press casting machine.

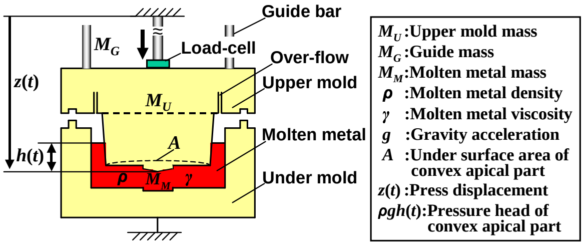


Figure 6: Outline of press process.

chine is shown in Figure 5. Figure 6 shows the illustration diagram of the press casting system. The molten metal is pressed by making the upper mold falling down towards the under mold. The upper mold consists of a greensand mold and a molding box. The upper mold has several passage parts in the convex part, which is called the over-flow as shown in Figure 6. The molten metal over the product volume flows into the over-flow part in the pressing.

The upper mold is moved towards up-and-down by using the press cylinder. The position of the upper mold is continuously measured by an encoder set in the servo cylinder. The position feedback control to obtain the desired behavior for the upper mold, is realized by using the PID controller. Then, the reaction force from molten metal is also measured by the load-cell installed on the servo cylinder.

3 MODELING OF PRESS PROCESS

3.1 Pressure Analysis by CFD

Visualization technology for observing time behavior of filling the fluid has been extensively developed. The pressure of molten metal in the mold during the press process is investigated by using commercial scientific software of CFD (Computational Fluid Dynamics). In this paper, FLOW-3D, a well-known CFD analysis software designed by FLOW SCIENCE Inc., is applied. The filling behavior analysis in press process is available by means of an expressive function of moving obstacle for the fluid.

To investigate the relationship between the load-cell response in experiments and the pressure behavior of molten metal using CFD, simulations using CFD and experiments using Figure 6 were conducted. As an example, simulation and experiment in the conditions of Table 2 were done. Here, the sampling period is 0.01[s], and the mesh block width is 2[mm] in CFD analysis. The relation between the calculated

Table 1: Simulation and experimental condition.

Press velocity; v	30[mm/s]
Pouring fluid mass; M_M	5.37[kg]
Pouring time; T_p	10.1[s]
Pouring fluid temperature; T_M	1405[°C]
Molten metal viscosity; γ	0.00235[Pa·s]

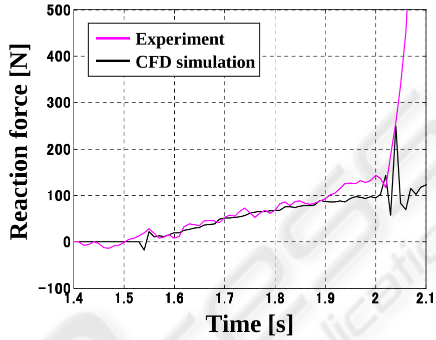


Figure 7: Comparison of reaction force between simulation and experiment.

pressure P_c[Pa] and the reaction force F_u[N] measured by load-cell is expressed by Eq.(1).

$$F_u = AP_c \qquad (1)$$

, where A[m^2] in Figure 6 is the under surface area of upper mold.

The comparative result is shown in Figure 7. In Figure 7, gray line is experimental result, and black line is simulation result using CFD. The upper mold touches at the molten metal in time of 1.52[s]. Concerning the time behaviors, the significant increasing reaction force appears at the time of about 2.03[s]. This time is approximately equal to the time when the molten metal flows into the over-flow parts. The high pressure of molten metal in the mold generates at this time. Subsequently, in the end period of press, the feature of the responses is greatly different. This is due to the gravity release by the upper mold sets on the under mold.

From Figure 7, the reaction forces measured in the both of CFD and experiments are thought to be approximately equal up to the 2.03[s]. Then, it was confirmed that the pressure calculated by CFD represented the actual pressure of molten metal in the mold.

3.2 Modeling with Respect to Pressure of Molten Metal

The pressure results by CFD analysis in the filling process well explained experimental results with high

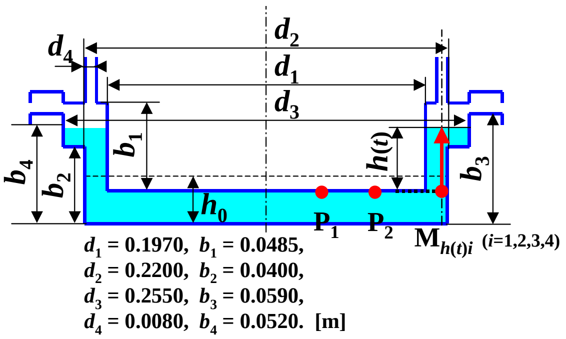


Figure 8: Shape of simplified casting mold shape.

reliability. However, press behavior cannot be calculated in real-time by the CFD analysis. The online estimation of pressure in the mold is required in the press casting system. The CFD is very effective to analyze the fluid behavior in off-line, and hence it is useful to predict the behavior and also optimize a casting plan. However, it is not enough for control design in real-time, because of calculation time. Therefore, we need to build a brief model for control design by using CFD simulation and experiment.

The estimation of the pouring volume is available by using the position data of the upper mold and estimating the contact time between under surface of the upper mold and the molten metal. They are measured respectively using the encoder and the load-cell. Then, to suitably realize the press velocity control without the excessive pressure, the estimation of pressure behavior is done by using the estimated data of pouring volume. From this reason, we build a mathematical model of molten metal pressure for the press velocity.

The mold shape used in authors study has a large convex parts with cross section of A as shown in Figure 6. To examine the pressure behavior for the genesis part of defect, a simplified mold shape plumbed the parts of curve, slope and draft angle for the primary mold shape. The simplified mold shape is shown in Figure 8, where b and d mean the height and the diameter respectively. $P_j(j$=1,2) are genesis parts of defect. The pressure fluctuation in press is represented by using a pressure model for the ideal fluid such that the incompressible and nonviscous fluid is assumed. Here, $h(t)$ in Figure 8 means the fluid level from under surface of upper mold. The head pressure P_j is directly derived from $h(t)$. The press distance $z(t)$ of upper mold is a downward distance from the position at the contact time of the poured fluid and the upper mold. As the press velocity increases, the dynamical pressure is varied by the effect of the liquidity pressure. Then, the hydrodynamic pressure for peak fluid height area is involved in P_j. Therefore, pressure P_b in P_j is consisted of head and hydrodynamic pressure, and is represented by Eq.(2).

$$P_b(t) = \rho g h(t) + \frac{\rho}{2}\dot{h}(t)^2 \tag{2}$$

The flow passage areas have three situations, *case* 1: $\pi(d_2-d_1)^2/4$, *case* 2: $\pi(d_3-d_1)^2/4$ and *case* 3: $n\pi d_4^2/4$, where the number n of the over-flow as diameter d_4 is equal to twelve. Figure 8 represents *case* 2. The following equations represent the fluid level variation in the each situation, and they are simply derived by assuming the incompressible fluid.

$$h(t) = \begin{cases} case\ 1: \ h(t) < h_{sw1}, \\ \frac{d_2^2}{d_2^2-d_1^2} z(t) \\ case\ 2: \ h_{sw1} \leq h(t) < b_1, \\ \frac{1}{d_3^2-d_1^2}(d_3^2 z(t) + d_1^2 h_{sw1}) \\ case\ 3: \ b_1 \leq h(t), \\ \frac{1}{nd_4^2}\{d_3^2 z(t) + (nd_4^2 - d_3^2) b_1\} \end{cases} \tag{3}$$

, where h_{sw1} and b_1 represent the threshold fluid level of $h(t)$ on *case* 1*case* 2, *case* 2*case* 3 respectively. h_{sw1} is expressed as follows. And,

$$h_{sw1} = \frac{d_2^2}{d_1^2}(b_2 - h_0) \tag{4}$$

, where h_0 means the initial fluid height before the upper mold touches to the molten metal. When the fluid height $h(t)$ equals to h_{sw1}, the equation of $h(t)$ changes from *case* 1 to *case* 2. Then, when $h(t)$ reaches to the height of b_1, $h(t)$ of Eq.(3) is changed from *case* 2 to *case* 3. As described the above, the pressure response for press velocity is determined from the both of initial fluid height and mold shape.

Eq.(2) or the mathematical pressure model of the molten metal in a mold is validated from the fluid behavior analysis by FLOW-3D on the filling in a press. Comparison of ideal fluid height $h(t)$ in a simplified mold and $h(t)$ in CFD simulation, is shown in Figure 9. As the CFD analysis results, height behavior of $M_{h(t)_i}$(: the measurement points of the over-flow) in Figure 8. The fluid height $h(t)$ for the parts of overflow is obtained. The press velocity is set as 5[mm/s].

When the ideal(incompressible and nonviscous) fluid height becomes steady-state response, the height in CFD results show the lower value of $h(z)$ due to the compression of the fluid by a gravity force. Next, pressure in the generation area of metal penetration defect is compared with a simplified mold.

The pressure behavior of P_2 in Figure 8 as the CFD result is shown, because the pressure response of P_2 is approximately equal to response of P_1, and area of P_2 is generation point of metal penetration defect. As comparing the results between CFD and a simply mathematical model, the pressure responses in press velocities of 5∼30[mm/s](5[mm/s] steps) are shown in Figure 10. The pressure performances of ideal fluid in the mathematical model are in excellent agreement with CFD analysis. Therefore, the pressure expressed by Eq.(2) is thought to be validated for the pressure of molten metal.

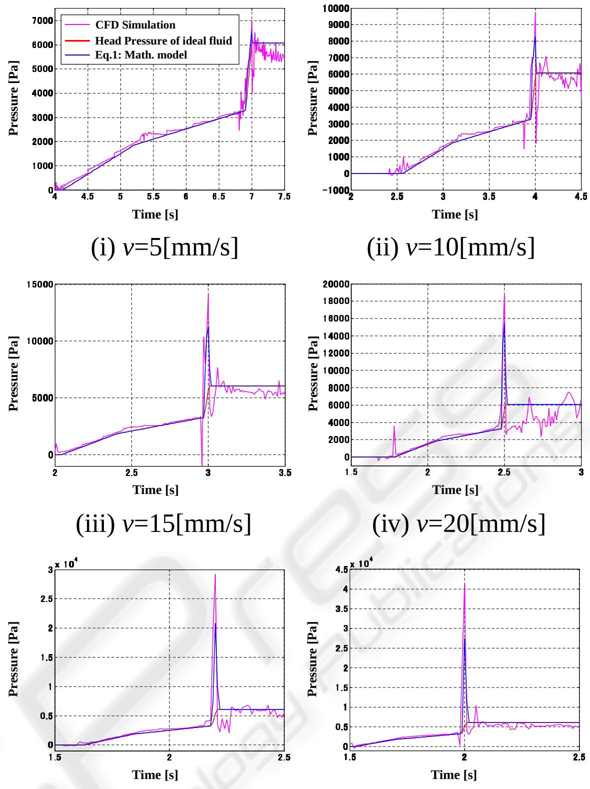
4 PRESSURE CONTROL

In this section, the simulation for suppression of rapid increase of pressure is executed using CFD analysis. It is already confirmed that the defect of metal penetration in a press process appears around over 80[mm/s]. In the case of over 80[mm/s], the defect is caused by rapid increase of pressure, when the molten metal flows arrives at the over-flow. Then, the switching action of press velocity at the time of the over-flow is started. The switching time is derived by using Eq.(3) and Eq.(4) of a simplified mold. In this pressure suppression simulation, the initial press velocity sets at 100[mm/s], and switches to the velocity of 10[mm/s] at the switching time of 1.29[s], where the initial fluid height of pouring outflow sets at 0.0192[mm]. Then, the calculated switching time is 0.14[s]. This switching time means the elapsed time, since the molten metal contacts with the under surface of the upper mold. The temperature of the molten metal in the mold is assumed to be about 1300[s].

The simulation results for pressure suppression in press process is shown in Figure 11. As seen from Figure 11, the fluctuation of pressure behavior using the switching control of velocity is dramatically smaller than that of non-switching case. In the time of 1.17[s], rapid excessive rise pressure is caused by the contact of molten metal with upper mold.

In the case of the constant velocity of 100[mm/s], the pressure peak value of 304080[Pa] is observed at the time of the over-flow. As seen from Figure 11, using the velocity switch from high-speed to low-speed at the specified time, rapid increase of pressure was drastically reduced. Then, press process time on this switch velocity is approximately equal to the time in press velocity of 80[mm/s] (time lag +0.015[s]). Velocity of 80[mm/s] is high speed press, and the defect of metal penetration is caused by high pressure due to this press velocity. By using the velocity switch from high speed to low speed, the press process of suppressing the pressure is realized in short time.

At this time, the control of press velocity pattern is decided by switching velocity obtained using tried and error method. In the near future, the newly proposed pattern of press velocity must be obtained by the optimal decision for the switching velocity. Furthermore, its validity must be demonstrated by actual



(i) v=5[mm/s] (ii) v=10[mm/s]

(iii) v=15[mm/s] (iv) v=20[mm/s]

(v) v=25[mm/s] (vi) v=30[mm/s]

Figure 10: Simulation Results of pressure behavior.

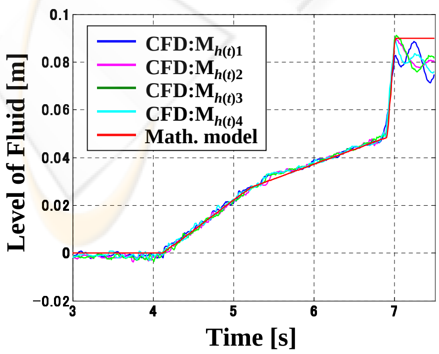


Figure 9: Fluid level in the case of v=5[mm/s].

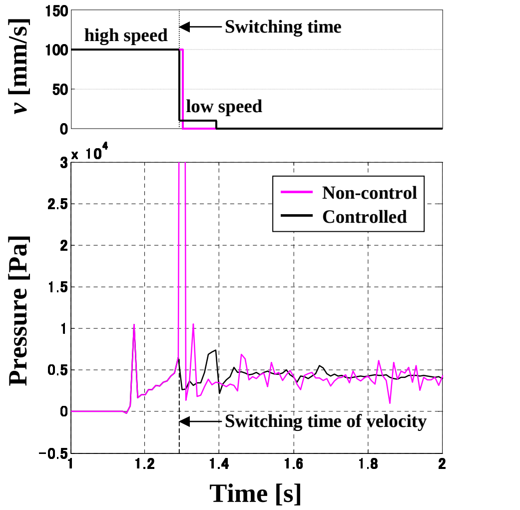


Figure 11: FLOW-3D simulation results of pressure control using switching of velocity.

experiments.

The molten metal in a mold is pressed by the upper mold by means of the position feedback control system using PID controller. The dynamical and static pressures are added as the disturbance elements in the middle of press process. In the near future, we advance the implementation using this pressure control system. Here, Figure 12 shows the block diagram of press casting system, where R_{Fout} means the reaction force from a load-cell. And, z_{in} and z_{out} are respectively reference and output position of the upper mold. M is total mass of the upper mold mass and the cylinder guide mass. W_1 and W_2 show the relation as follows.

$$W_1 : z(t) \longrightarrow h(t), \qquad W_2 : \dot{z}(t) \longrightarrow \dot{h}(t)^2 \tag{5}$$

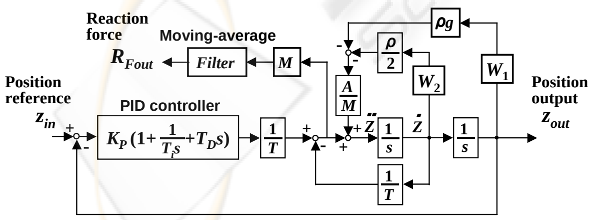


Figure 12: Block diagram of press control system in a press casting method using greensand molding.

5 CONCLUSION

In this paper, in order to realize the pressure control by controlling a press velocity, a design method of press velocity pattern for high speed press control with the reduction of rapid increase of pressure inside a mold has been proposed. Then, a mathematical model for the pressure of the molten metal in a mold was built. This model showed its effectiveness by using CFD analysis. Next, a switching pattern of press velocity from the high speed to low speed was derived from the simplified mold obtained to reduce the rapid increase of pressure. Using the obtained velocity pattern, the press control simulation has been done by CFD analysis. Good control results have been performed by the proposed method.

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