Modelling and Control of Pressurized Molten Metal in Press Casting *

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Abstract: This paper presents a modeling and control of molten metal's pressure in a pressing process using an innovative iron casting developed by our group. In this method, molten metal is directly poured into the lower mold, and then pressed to fill the cavity by the upper mold being lowered down. For the complex liquid flow during pressing, the liquid's pressure change inside vertical path with various contraction and expansion geometries is newly modeled via the unstationary Bernoulli equation. The mathematical model is derived for a control design of pressing. To conduct the pressing velocity design algorithm, an unknown parameter of proposed model considering viscous flow is identified by using CFD: Computational Fluid Dynamics model with heat flow calculation. Control performance using a multi-switching velocity pattern is confirmed as an effective control design using the pressure model, because the pressure fluctuation has discontinuous variation points. Substituting detailed information for mold shape, poured volume and initial temperature into a developed control input generator, an optimum pressing velocity design and a robust design for defect-free production are proposed by the design algorithm based on the construction of an inverse system comprised of the sequential switching from higher to lower speed. Consequently, the effectiveness of the pressing control with reasonable pressure suppression has been demonstrated through the CFD simulation.

Keywords: Pressure control, Physical models, Metals, Viscous friction, Process parameter estimation, Sequential switching, Industrial production systems

1. INTRODUCTION

A new casting method, called the press casting process, has been developed by our group in recent years. In this process, the ladle first pours molten metal into the lower (drag) mold. After pouring, the upper (cope) mold is lowered to press the metal into the cavity. This process has enabled us to enhance the production yield rate from 70% to over 95%, because a sprue cup and runner are not required in the casting plan (See Terashima (2009)). In the casting process, molten metal must be precisely and quickly poured into the lower mold. Weight controls of the pouring process have been proposed in very interesting recent studies by Noda et al. (2006 and 2007). However, in the pressing part of the casting process, casting defects can be caused by the pattern of pressing velocity. For example, the brake drum shown in Fig. 1 was produced by the press casting method. Since the molten metal was pressed at high speed, the product had a rough surface. This type of surface defect in which molten metal seeps through sand particles of the greens and mold and then solidifies, is called

* This work was supported in part by "Japan Society for Promotion of Science: JSPS fellows" and also "Global COE Program of Frontiers of Intelligent Sensing" from the Ministry of Education, Culture, Sports, Science and Technology, Japan. Metal Penetration. Metal penetration is most likely caused by the high pressure that molten metal generates, and it necessitates an additional step of surface finishing at the least. Thus, the product quality must be stabilized by the suppression of excess pressure in the high-speed press. For short-cycle-time production, a high-speed pressing control that considers the fluid pressure in the mold is needed.

Pressure control techniques have been proposed for different casting methods (See Louvo et al. (1990) and Mickowski et al. (1993)). In the injection molding process, the pressure control problem has been successfully resolved by computer simulation analysis using optimization technique by Hu et al. (1994) and Terashima et al. (1999). Furthermore, a model based on PID gain selection has





been proposed for pressure control in the filling process. Although the pressure in the mold must be detected in order to control the process adequately using feedback control, it is difficult to measure the fluid pressure, because the high temperature of the molten $metal(T \ge 1400(K))$ precludes the use of a pressure sensor. Thus, in our previous papers by Tasaki et al. (2008), the pressure during pressing at a lower pressing velocity was estimated by using a simply constructed model of molten metal's pressure based on results of the CFD analysis. A new sequential pressing control, namely, a feedforward method using a novel simplified press model, has been reported by the authors. It has been shown that this method is very effective for adjusting pressure in a mold. However, in the previous paper, the actual unstationary flow and the temperature drop during pressing was not considered; a detailed analysis that considers the temperature change during pressing is required to reliably predict and control the process behaviors.

This paper presents a multi-switch system of controlling the pressing velocity using a newly constructed model in which the fluid shear stress is considered to be strongly related to the increasing pressure during high-speed pressing. Here, a novel mathematical model with the pressure loss term of fluid in vertical unstationary flow is derived by assuming that the incompressible viscous flow depends on the temperature drop of the molten metal. The model error for the real fluid's pressure is minimized by the use of parameter identification for the friction coefficient at the wall surface (the sole unknown parameter). Furthermore, the designed velocity of the switching pattern is sequentially calculated by using the maximum values of static, dynamic, and friction pressure, depending on the situation in each flow path during the press. An optimum design and a robust design of pressing velocity using a switching control are proposed for satisfying pressure constraint and shortening the operation time. As a final step in this study, we used CFD simulations to check the control performance using the obtained multi-step pressing pattern without a trial-and-error process.

2. PRESSING PROCESS IN PRESS CASTING

The upper mold consists of a greensand mold and a molding box. The convex part of the upper mold has several passages that are called overflow area, as shown in Fig. 2. Molten metal that exceeds the product volume flows into the overflow areas during pressing. These areas are the only parts of the casting plan that provide the effect



Fig. 2. Diagrammatic illustration of pressing

of head pressure. As the diagram shows, these are long and narrow channels. When fluid flows into such an area, high pressurization will cause a casting defect. Therefore, it is important to control the pressing velocity in order to suppress the rapid increase in pressure that occurs in high-speed pressing. The upper mold moves up and down by means of a press cylinder and servomotor. The position of the upper mold can be continuously measured due to an encoder set in the servo cylinder to control molten metal pressure using switching velocity.

3. MODELLING OF PRESSURIZED MOLTEN METAL

The online estimation of pressure inside the mold is necessary in the press casting system. The CFD analysis, based on the exact model of a Navier-Stokes equation, is very effective for analyzing fluid behavior offline and is useful for predicting the behavior and optimizing of a casting plan (See Galaup et al. (1986) and Ohnaka (2004)). However, it is not sufficient for the design of a pressing velocity control or for the production of various mold shapes, because the exact model calculation would take too much time. Therefore, construction of a novel simple mathematical model for the control design in real time is needed in order to realize real-time pressure control.

3.1 Unstationary Flow in Vertical

To analyze moving fluid motion during pressing, several experiments with colored water and an acrylic mold have been carried out as shown in Fig. 3.

The nature of flow will dictate the choice- rectangular cartesian, cylindrical, spherical etc. In a 3D flow, velocity components exist and change in all three dimensions, and are very complicated to study. In the majority of engineering problems, it maybe sufficient to consider 2D flows. Therefore the acrylic mold shaped flat is prepared for flow observation of liquid. The main purpose of our study on the press casting process is to suppress the defect generation of casting product. Air Entrainment during filling is one of the most important problems to solve for flow behavior by adjustment of pressing velocity. If the air is included in molten metal, it will stay and be the porosity defect. By the experimental result, upper mold velocity less than 50(mm/s) of pressing without air entrainment is confirmed. From this fact, the pressure model construction is considered for only unstationary flow in vertical without air entrainment, or the pressing velocity lower than the upper limit for the defect free for air entrainment.



Fig. 3. Observational experiment of unstationary flow

3.2 Pressure Model in Press Casting

Fig. 4 shows the rising flow during pressing and each stream line of molten metal's flow. The unstationary Bernoulli equation for two points: S and B on a given stream line in the flow of an incompressible fluid in the presence of gravity is

$$\int_{B}^{S} \frac{\partial U}{\partial t} ds + \frac{1}{2}U_{S}^{2} + \frac{P_{S}}{\rho} + ge_{S} = \frac{1}{2}U_{B}^{2} + \frac{P_{B}}{\rho} + ge_{B}, \quad (1)$$

where $\rho(kg/m^3)$ is the density of fluid and $g(m/s^2)$ is the acceleration of gravity. The integral is taken along the stream line, and cannot be easily evaluated in general. For the rising flow in press casting, the integral can be quite closely approximated by an integral along the vertical axis. In the case of Fig. 4, the stream line is taken to vertically extended from the bottom surface of upper mold to the free surface of fluid. Placing the origin to the bottom of upper mold surface, substituting $P_S = 0$ (based on gauge pressure) and $e_h = e_S - e_B$, and neglecting \dot{e}_B^2 as $\dot{e}_S^2 \gg \dot{e}_B^2$, then the equation (1) simplifies to

$$P_B = \rho \left(\ddot{e}_h e_h + \frac{1}{2} \dot{e}_h^2 + g e_h \right).$$
⁽²⁾

The fluid velocity $\dot{e}_h(m/s)$ at the free surface $A_S(m^2)$ relates the mold surface area $A_M(m^2)$ at the same height with the free surface and the pressing velocity \dot{z} as shown in Fig. 4. This velocity relational equation is as follows.

$$\dot{e}_h(t) = \frac{A_M(e_h)}{A_S(e_h)} \dot{z}(t) \tag{3}$$

Here, rewriting the extended Bernoulli equation in terms of z(m) and considering with the initial volume of fluid poured in the lower mold, one obtains

$$P_B = \rho \frac{A_M^2(e_h)}{A_S^2(e_h)} \left(\ddot{z}z + \frac{1}{2}\dot{z}^2 \right) + \rho g f(V_p, z) + \Delta p(T, e_h), (4)$$

where $\Delta p(T, e_h)$ means a pressure loss depended on liquid temperature change on the flow from upstream to downstream and the vertical flow length e_h contacting with the wall.



Fig. 4. Change of stream line of rising liquid

To confirm the proposed pressure model for pressed liquid, several experiments using simplified shape mold and water have been carried out. The acrylic mold and its shape are shown in Fig. 5. The vertical movement of the upper mold is derived accurately for reference input of velocity curve by servo-press system. In the experiment as shown in Fig. 6, the actual pressing velocity(solid line) is reshaped for reference input(dashed line). This slight difference is due to the driving motor characteristic approximated by firstorder lag element with the time constant: 0.020(s). As an



Fig. 5. Mold shape for a part of overflow



Fig. 6. Pouring and pressing processes in press casting

example of the confirmation result with proposed model, pressure behavior measured by piezoelectric-type pressure sensor(AP-10S, by KEYENCE Corp.) is shown in Fig. 6(lower), solid line. Here, the maximum pressing velocity is set to 20(mm/s), and total moving displacement of press is 22(mm). The dashed line in Fig. 6 (lower) is the pressure calculated result with Bernoulli's equation for steady fluid flow as described. As seen from this figure, the calculated result of the proposed pressure model considering the unstationary flow, is in excellent agreement with actual pressure behavior during pressing.

3.3 Viscous Influence

In a practical situation, the temperature decrease due to the heat transfer between the molten metal and the mold surface should be considered as an important influence on liquid pressure during pressing. For decreasing temperature , the viscosity increase and higher pressure are then generated, and therefore the penetration defect occurs. Generating the shearing force on the wall surface of the flow path, a point at the upstream is pressurized higher than one at the downstream. Considering the pressure difference between P_B at the bottom of the upper mold and P_S at the free surface, it is written as $\Delta p = P_B - P_S$. Here, the equilibrium relation of force between the shearing force F_w and the Δp is derived as following equation by considering the pressure loss.



Fig. 7. Simplified casting mold of brake drum

$$F_w = \frac{\pi}{4} (d)^2 \Delta p = \pi dl \tau \tag{5}$$

Here, using the friction coefficient λ depended on molten metal's temperature T(K), Δp can be represented by the following equation.

$$\Delta p(T, e_h) = \rho \frac{A_M^2(e_h)}{A_S^2(e_h)} \frac{\lambda(T)l(e_h)}{2d(e_h)} \dot{z}^2 \tag{6}$$

After substituting (6) to (4), the proposed pressure model conformable to the complex model of CFD is constructed by depending on liquid temperature to express more precisely the molten metal's pressure. Here, $\lambda(T)$ means the coefficient of fluid friction depending on the fluid temperature; it will be an unknown parameter of the proposed model. $l(e_h)$ is the mold wall length of the part that causes shear stress in the vertical direction. D_i (i=1,2,3) represents the surface area of the flow channel decided by the mold shape as shown in Fig. 7, and D_i will change as $D_1 = d_2 - d_1, D_2 = d_3 - d_1, D_1 = d_4/n$ during pressing. n is the number of overflow areas. By the pressing velocity term in the newly proposed pressure model, it is easily understood that P_B will be rapidly rising due to the increasing fluid velocity when fluid flows into narrow flow path areas.

4. SWITCHING CONTROL OF PRESSURE

We have proposed a switching control for the pressing velocity to suppress the pressure increase. Thus, the pressing velocity necessary to suppress the pressure for defect-free production must be determined and implemented. Here, a multi-switching velocity pattern can be obtained using the following equation, and derived from the pressure model.

$$\dot{z}_k = \sqrt{\frac{2\left(P_{B\,\text{lim}} - \rho g h_{uk}\right)}{\rho \max\left(A_{Mk}^2/A_{Sk}^2\right)\left(1 + \lambda(T)h_{uk}/D_k\right)}} \tag{7}$$

The $k_{th}(k = 0, 1, ...)$ -step velocities are decided in order that the maximum velocity satisfies the desired pressure constraint $P_{Blim}(Pa)$. Because the diameter D_k and square ratio of surface area $(A_{Mk}/A_{Sk})^2$ discontinuously change by each stage during pressing as shown in Fig. 7, a multi-switch velocity control is adopted. The number kof steps of pressing velocity with multi-switching can be determined by the mold shape in the case of Fig. 7, with the maximum value of k being 3. Initial pressing velocity \dot{z}_0 will be the upper limit velocity for defect free of air entrainment discussed in section 3.1. The limit velocity drives until the displacement when the bottom surface of the upper mold contacts the top surface of the poured



Fig. 8. Pressing input by trapezoidal velocities



Fig. 9. Pressure suppression $(T_{const.} = 1673(K))$

fluid in the lower mold. Derivation of (7) is straightforwardly calculated, and is omitted due to the paper space limitation.

When the pressing velocity changes from \dot{z}_k to $\dot{z}_{k+1}(m/s)$, the pressing distance z(m) is given by information of the mold shape and poured fluid volume. The design of the sequential velocity pattern such as the multi-switch point and each velocity must be adapted to particular mold shape. In the next pressing simulation, a switching velocity input is sequentially designed as shown in Fig. 8, where the press velocity pattern is formed as a trapezoidal shape by the switching position H_{uk} and the pressing acceleration $\ddot{z}(m/s^2)$. The control performance using the switching velocity of (7) designed by the proposed simple model was reasonably validated by the CFD simulation as shown in Fig. 9. Although the flowing fluid has 3 flow pass stages during pressing for the mold shown in Fig. 7, the designed switching velocity pattern switches only once. This is meant to set a maximum velocity of 50(mm/s) for \dot{z}_1 at the 1st stage and \dot{z}_2 at the 2nd stage to suppress extremely turbulent flow. \dot{z}_3 at the 3^{rd} stage of the narrow flow pass is then designed to 6.9(mm/s). Here the pressing acceleration is set to $1.5(mm/s^2)$, and

Table 1. Molten metal's properties in CFD simulation

Simulation	
Density	$7000 \ (kg/m^3)$
Viscosity(T = 1673(k))	$0.02 \ (Pa \cdot s)$
Viscosity(T = 1423(k))	$0.20 \ (Pa \cdot s)$
Specific heat	711 $(J/(kg \cdot K))$
Thermal conductivity	29.93 $(W/(m \cdot K))$
Heat transfer	$1000 \ (W/(m^2 \cdot K))$
Liquidus temperature	1473 (K)
Solidus temperature	1438.15~(K)
Surface tension coefficient	1.8(-)
Contact angle	90(deg)



Fig. 10. Friction parameter identification

the total distance of pressing is 15(mm). The molten metal properties in CFD simulations are shown in Table 1. Both pressure fluctuations as shown in Fig. 9 are satisfied under the pressure constraint value assumed as 10(kPa). This pressure constraint value has been previously decided by using both the actual experimental test and the CFD analysis results of the press with several constant velocity patterns using molten metal.

In the next, parameter identification of $\lambda(T)$ will be done for each simulation condition to consider the pressure increase suppression for viscous fluid with a temperature decrease. Pressure has been rapidly increased while liquid flows into narrow pass $d_3(e_h)$ such that stage-3. As seen from (4) and (6), the effect of $\lambda(T)$ on the variation of pressure $P_b(t)$ becomes drastically larger with the increase of liquid level $e_h(z)$ and flow velocity $\dot{e}_h(\dot{z})$. Thus, exact value of $\lambda(T)$ must be given for the region of e_h and \dot{e}_h , because our main purpose is to suppress the maximum pressure value for pressure fluctuation. Therefore the fitting parameter identification should be considered for only the flow during a short period in stage-3. Then, T_{end} is the lowest temperature during pressing because of the end time of pressing.

Several parameter identifications of the fluid friction coefficient $\lambda(T_{end})$ at end time of pressing for various upper mold velocities have been carried out by comparing the proposed model with the CFD model analysis. The conditions of molten metal in these identification simulations are shown in Table 1. For the assumption of temperaturedrop cases, initial temperatures are set at 1673, 1623 and 1573(K) respectively. Although the inverse trend of relative change between temperature-drop and viscosityincrease have been clarified, it seems difficult to obtain analytical theoretical equation analytically on the relative changes for a wide range of temperature variations and a variety of materials. In the temperature drop from 1673 to 1423(K), the viscosity increase is arbitrarily assumed as the linearly dependence changing from 0.02 to $0.20(Pa \cdot s)$. Here, the maximum value of the pressure behavior by (4)and (6) of the proposed model is uniquely fitted to the results of the CFD model simulation.

In each case, the time-invariant parameter $\lambda(T_{end})$ has been identified as shown in Fig. 10. Using the designed velocity pattern in Fig. 9 conducted under the condition of constant temperature during pressing, the pressure behavior considering the fluid's heat flow to the molds exceeds the pressure constraint (top in Fig. 10) because of the higher viscosity (bottom in Fig. 10). Comparing the each result in Fig. 10, the lower temperature at end time induces the larger the value of $\lambda(T_{end})$. The temperature drop from start to end of pressing is almost 50(K) in these results. The pressure increase during pressing due to the larger value of $\lambda(T_{end})$ with the decreased temperature is confirmed. The simulation results of a simple model such that $\lambda(T_{end})$ is given as a constant value by fitting almost explains the results of the CFD model. Therefore, it is expected that we can conduct the control design using this simple pressure model under the restricted temperature change.

5. PROPOSED CONTROL DESIGN AND RESULTS FOR PRESSURE SUPPRESSION

In this section, the proposed sequential switch velocity control considering the viscosity increase related to the temperature drop during pressing will be checked by using CFD model simulation with heat flow calculation. For example, for the designed pressing velocity patterns using $\lambda(T_{end})$ derived by the previous simulations, where T_{end} =1622, 1574 and 1522(K), the pressure suppression resultsfor the each temperature condition of $T_{initial} = 1673, 1623$ and 1573(K) were checked for a upper pressure constraint: 10(kPa). Here, optimum design and robust design are respectively introduced by using the proposed switching control method. Fig. 11(upper) shows a comparison of the designed velocity patterns and the magnified view. These lines show designed optimum velocities in the each case of temperature drop. The switched constant velocities $(2^{nd}$ pressing velocity) are slightly different as 6.2, 5.5 and 5.2(mm/s), for the influence of the viscosity increase with the temperature drop. The end time of pressing are then 0.520, 0.546 and 0.560(s) respectively, and the maximum difference of the pressing time is only 0.040(s). These velocity patterns which differs slightly, guarantees



Fig. 11. Pressure suppression in the case of optimum design



Fig. 12. Pressure suppression in the case of robust design

the exact suppression of pressure less than the constraint value as shown in Fig. 11(lower). Fig. 11(bottom) shows the magnified view of the pressure peak part at the end time of pressing. On the other hand, Fig. 12 shows pressure suppression validation for a robust design of pressing velocity. The designed velocity by $\lambda(T_{end}) = 1522(K)$ in case of lowest temperature has been checked for $T_{initial} = 1673$, 1623 and 1573(K). As seen from Fig. 12(bottom), each maximum pressure value is suppressed under the upper constraint of pressure with some allowance. However, the end time is a little bit longer compared with the optimum design case. As seen from this result, both methods satisfies the pressure suppression. However, optimum design satisfies both requirements of pressure constraint and shortening the operation time. On the other hand, robust design satisfies only pressure constraint, although this is useful, when temperature drop is not exactly known, but knows the least temperature for all batch operations. The analysis presented concludes that the proposed control to suppress the maximum pressure of viscous flow with temperature drop can design the press switching velocity pattern optimally and robustly, for such the case that temperature drop from start time to end time of press is about 50(K).

6. CONCLUSION

In this paper, a mathematical modeling and a switching control for pressure suppression of pressurized molten metal were discussed for defect-free production using the press casting. For the complex liquid flow inside vertical path during pressing, the liquid's pressure model for the control design was newly proposed via the unstationary Bernoulli equation, and was represented in excellent agreement with actual pressure behavior measured by a piezoelectric-type pressure sensor. Next, the sequential pressing control design with switching velocity for the high-speed pressing process that limits pressure increase, was applied with considering the influence of viscous change by temperature drop. Using the pressure constraint and information on the mold shape, an optimum velocity design and robust velocity design were derived respectively without trial-and-error adjustment. Consequently,

the effectiveness of the pressing control with reasonable pressure suppression has been demonstrated through the CFD simulation. In the near future, the proposed pressure model for optimizing the pressing process will be modified with the theoretical function models on temperature and viscosity-change, and furthermore real experiments with molten metal will be done.

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REFERENCES

- K. Terashima, Y. Noda, K. Kaneto, K. Ota, K. Hashimoto, J. Iwasaki, Y. Hagata, M. Suzuki and Y. Suzuki. Novel Creation and Control of Sand Mold Press Casting "Post-Filled Formed Casting Process". Foundry Trade Journal International (The Journal of The Institute of Cast Metals Engineers), No.183 (3670), pages 314-318, 2009.
- Y. Noda, M. Suzuki and K. Terashima. Optimal sequence control of automatic pouring system in press casting process by using greensand mold. *Proc. of SICE-ICASE International Joint Conference*, pages FE06-4. Busan, Korea, 2006.
- Y. Noda and K. Terashima. Modeling and feedforward flow rate control of automatic pouring system with real ladle. *Journal of Robotics and Mechatronics*, vol.19(2), pages 205-211, 2007.
- Louvo A, Kalavainen P, Berry J. T and Stefanescu D. M. Methods for ensuring sounds SG iron castings. *Trans. of American Foundry Society*, vol.98, pages 273-279, 1990.
- Mickowski J. R and Teufert C. E. The control of impact pressure in the high pressure die casting process. *Trans* 17th Int. Die Cast Congress and Exposition, pages 349-354, 1993.
- Hu J and Vogel J. H. Dynamic modeling and control of packing pressure in injection molding. In Journal of Engineering Materials and Technology, vol.116, No.2, pages 244-249, 1994.
- K. Terashima, H Nomura, Y. Maeda and R. Katoh. Simulation and optimization on injection velocity's switching in cavity filling process. In Proc. of 14th International Federation of Automatic Control, Vol.18, pages 31-36, Beijing, China, 1999.
- R. Tasaki, Y. Noda, K. Terashima and K. Hashimoto. Sequence control of pressing velocity for pressure in press casting process using greensand mould. *International Journal of Cast Metals Research*, Science and Engineering of Cast Metals, Solidification and Casting Processes, AFC-10 Special Issue, vol.21(1-4), pages 267-274, 2008.
- C. Galaup, U. Dieterle and H. Luehr. 3d visualization of foundry molds filling. *In Proc. of 53rd International Foundry Congress*, pages 117-127, Prague, Czech, 1986.
- I. Ohnaka. Development of the innovative foundry simulation technology. In Journal of the Materials Process Technology, "SOKEIZAI", vol.45, No.9, pages 37-44, 2004.