Proceedings of the 72nd World Foundry Congress
21-25th May 2016, Nagoya, Japan

# Optimum Feedforward and Model Predictive Control of Molten Metal Pressure in Greensand Mold Press Casting

*T. Takahito[1], R. Tasaki[1], K. Hashimoto[2] and K. Terashima[1]
[1] Department of Mechanical Engineering, Toyohasi University of Technology,
Hibarigaoka 1-1, Tempaku, Toyohashi, 441-8580, Japan
[2] Sintokogio, Ltd., Honohara 3-1, Toyokawa 442-8505, Japan
*E-mail: takako@syscon.me.tut.ac.jp

This paper presents a novel technique for controlling the molten metal pressure in the casting production process, in order to realize high productivity and high-quality castings. We propose a pressure feedback control design using a model predictive control method (MPC), and also present a simulation study. The MPC method is a useful control technique that predicts a future pressure by using the nominal model. Several experiments have been done to demonstrate the effectiveness of the proposed approach comprising optimum feedforward control and model predictive feedback control. Good performance has been achieved with respect to both high-speed response and robustness for model uncertainty.

***Keywords:*** *Press casting, Quality control, Pressure control, Model predictive control, Parameter identification*

## 1. Introduction

The greensand press casting method is a novel technique for controlling the molten metal pressure in the casting production process. Moreover, this is a high-speed, high-quality method capable of achieving a production yield exceeding 90%. In greensand mold press casting, for which our group invented this novel process [1], molten metal is first poured into a lower mold, then the upper mold is lowered toward the lower mold, and finally the two molds are matched. Since casting defects such as physical metal penetration, are often caused by the high pressure in a high-speed pressing process, pressure control is needed for defect-free production. However, direct measurement of liquid pressure, such as by a contact-type pressure sensor, is difficult in a high-temperature metal process.

Feedforward control cannot adapt to viscosity change dependent on temperature. Tasaki et al. proposed sequential pressure control by feedforward control [2]. But there are some problems concerning control time, disturbance, and robustness for model uncertainty. Hence, in this paper, we present a new method to estimate the in-mold pressure using the pressing reaction force from load-cell, and then construct a press feedback control system.

## 2. Press casting process

The system configuration and the experimental equipment used in this study are shown in Fig. 1. We set up a servo drive pressing machine, a transparent acrylic mold, and colored and viscous water with CMC: carboxymethylcellulose. The actual liquid pressure inside the mold can be measured by a contact-type sensor of a pressure gauge. Moreover, we measure the reaction force of the molten metal using a force sensor installed between the upper mold and the lifting device. Then we can estimate the pressure using a reaction force of the molten metal. A feedback control system using the estimated pressure is newly constructed for continuous high-quality production.

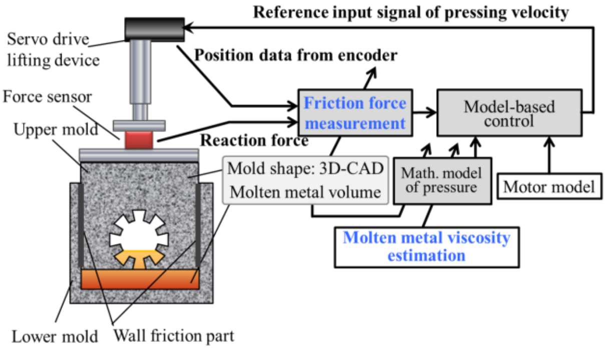

Fig. 1 Pressing casting process with pressure feedback control system

## 3. Pressure estimation

During pressing, wall frictional resistance generated between the upper mold and the lower mold, is an unpredictable disturbance for pressure estimation. Considering the force-pressure relation, the actual pressure can be estimated from Eq. (1) by subtracting frictional resistance from the force sensor, as follows:

$$P = (F - mg - m\ddot{z} - \mu(\dot{z})Lz)/A, \qquad (1)$$

$$\mu(\dot{z}) = \begin{cases} \mu_d & (|\dot{z}| > \dot{z}_{lim}) \\ \mu_s - \frac{\mu_s - \mu_d}{\dot{z}_{lim}}|\dot{z}| & (otherwise) \end{cases} \qquad (2)$$

where, Eq. (2) is the mathematical model of frictional resistance, molten metal pressure: $P$(Pa), force sensor value: $F$(N), the upper mold mass: $m$(kg), gravitational acceleration: $g$(m/s$^2$), the upper mold position: $z$(m), speed: $\dot{z}$ , acceleration: $\ddot{z}$ , the friction coefficient $\mu(\dot{z})$ ( - ), friction part length: $L$(m) and the cross-sectional area of upper mold: $A$(m$^2$).

An example of the pressure estimation result in pressing experiments with viscous water is shown in Fig. 2. The dashed-dotted line is actual pressure measured by the contact-type sensor, the dotted line is measured pressure from a force sensor, and the solid line is observed pressure by the proposed estimation method during pressing.

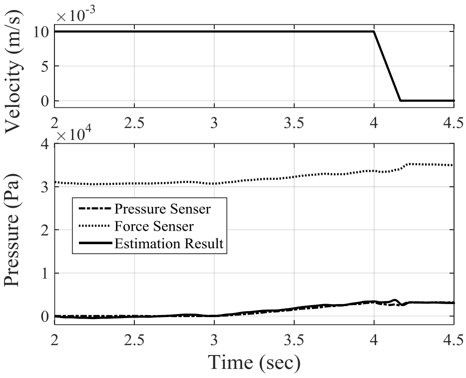

Fig. 2 Pressure estimation result

## 4. Viscosity estimation

In the pouring process before pressing, poured molten metal is often subject to volume error or temperature change. Therefore, the parameter of volume $V_p$ (m$^3$) and viscosity $\lambda$ related to temperature $T$ (degrees C) must be identified for high-quality iron casting and construction of the MPC system in our study. The base model for MPC is derived by the extension of Bernoulli's theorem, represented by

$$P_B = \rho \frac{A_M^2(e_h)}{A_S^2(e_h)} \left( \ddot{z}\, z + \left( \frac{1}{2} + \lambda(T) \frac{L(e_h)}{D(e_h)} \right) \dot{z}^2 \right) + \rho g f(V_p, z) \tag{3}$$

As shown in Eq. (3), the pressure estimation requires information of $z$, $\dot{z}$ , $\ddot{z}$ , $V_p$ and $\lambda$. These unknown parameters can be identified by fitting calculation using the method of least squares. Here, the observed data by Eq. (1) and the model output by Eq. (3) for pressure behavior within a specified short time at the beginning of pressing are used. Table 1 shows the parameter identification results for each condition of viscosity $\eta$ = 0.001, 0.5, 1.0, 5.0 and for a setup liquid height $h_0$ = 0.05(m).

Table 1 Identified parameters

| Actual viscosity $\eta$ (Pa・s) | Viscosity: $\lambda$ | Volume: $V_P$ (m$^3$) | Initial liquid height: $h_0$ (m) |
|---|---|---|---|
| 0.001 (water) | 0.9 | 0.406 | 0.0518 |
| 0.5 | 2.0 | 0.408 | 0.0520 |
| 1.0 | 2.6 | 0.417 | 0.0532 |
| 5.0 | 6.9 | 0.422 | 0.0538 |

## 5. Model predictive control (MPC)

Pressure control must be satisfied under the pressure constraint condition for high-quality sand mold casting. The MPC method predicts the future output first, calculates the optimum input for keeping the constraint, and then realizes good performance of the real output.

In our MPC approach, we build linear predictive model control that is calculated at high speed, therefore is effective in real-time feedback control.

Eq. (4) is the response of the system. The response $\boldsymbol{\tau}$ should be equal to the reference pressure trajectory $\boldsymbol{\tau}_r$,

$$\boldsymbol{\tau} = \boldsymbol{y}_f + \boldsymbol{S}\boldsymbol{u} \tag{4}$$

the optimal control input $\boldsymbol{u}$ is given by

$$\boldsymbol{u} = \left(\boldsymbol{S}^{\mathrm{T}}\boldsymbol{S}\right)^{-1}\boldsymbol{S}^{\mathrm{T}}\left(\boldsymbol{\tau}_r - \boldsymbol{y}_f\right) \tag{5}$$

where $\boldsymbol{y}_f$ is the free response in the future, $\boldsymbol{S}$ is the unit step response matrix. The MPC simulation result is shown in Fig. 3. This simulation result confirm that the MPC is very effective for the liquid pressure control during pressing in the press casting process.

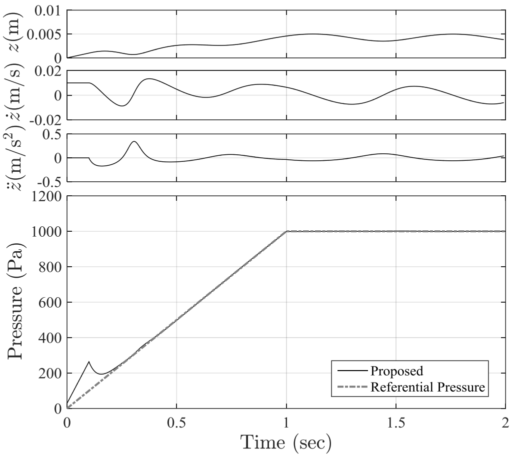

Fig. 3 MPC simulation result

## 6. Conclusion

We proposed a pressure feedback control system using MPC in this paper, and also showed its good performance, namely new process of continuous high-quality iron casting. We are now preparing comparative experiments for the optimum feedforward control and our proposed feedback MPC in our laboratory.

## References

[1] K. Terashima, et al.: Novel Creation and Control of Sand Mold Press Casting "Post-Filled Formed Casting Process", Foundry Trade Journal International (2009), 183 (3670), pp. 314-318

[2] R. Tasaki, et al.: Modelling and Control of Pressurized Molten Metal in Press Casting, Journal of Mechanics Engineering and Automation (2012), Vol.2, No.2, pp. 77-84