AMM009

Control of Plunger Injection Velocity for Die Casting Considering Inflow of Molten Metal

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Abstract

Die casting is a casting process in which a plunger injects molten metal into a mold with high pressure and high speed. Plunger injection sometimes prompts air entrapment and temperature decrease and, as a result, casting defects occur in the die casting products. In order to counter these, control of plunger injection is required; specifically, injection must be faster and there must be no air entrapment.

Recently, we achieved a new type of plunger injection control that improves plunger injection input by estimating the molten metal behavior with a computational fluid dynamics (CFD) simulator. In conventional plunger injection control, the injection starts with the molten metal set in a hydrostatic state in the sleeve. Therefore, to the best of our knowledge, the ruffle of molten metal that arises during the pouring process has not yet been examined, nor has the phenomenon been adequately described.

In this study, we first validated the effect of the ruffle of molten metal that arises upon pouring on the quality of die casting products. We then evaluated molten metal behavior by simulating the pouring and injection processes. We also examined the validity of the evaluation method by comparing analytical and experimental results. Finally, we designed a control input for plunger injection taking the pouring of molten metal and the waiting time into consideration.

***Keywords**:* die casting, plunger injection control, computational fluid dynamics, response surface method

1. Introduction

Die casting is a casting method that can produce a smooth casting product with a high degree of accuracy. However, because a plunger injects molten metal into a mold with high pressure and high speed, die casting has the disadvantage that casting defects such as blowholes and cold flakes may occur in the product. A casting defect may significantly compromise the mechanical properties of the product.

Injection velocity control of the die casting plunger is one of the countermeasures that may be taken against casting defects in die casting products. In recent years injection velocity control during die casting has been examined: fluid behavior is estimated at the time of plunger injection using a computational fluid dynamics (CFD) simulator, and plunger injection velocity input has been improved using the analysis results [1-3]. In the past, the molten metal was set in the sleeve under static conditions and was then injected into the mold under injection velocity control. However, the wave caused in pouring was not taken into consideration and the actual phenomenon was therefore not adequately described.

In the present study, we first examined the effect of the ruffle of molten metal that occurs when pouring on the quality of the product. We then designed a control input for plunger injection taking into consideration the pouring of the molten metal and the waiting time from the completion of pouring to the initiation of injection (shot time lag). For fluid analysis and the evaluation of air entrapment in this study, we used the FLOW-3D software made by Flow Science, Inc.

2. Experimental equipment

In the present study, we used a die casting machine whose mold locking force was 135 t. This die casting machine can set plunger injection velocity from 0.05 m/s to 6.0 m/s and speed switching is configurable. It also sets the shot time lag at intervals of 0.1 s. This pouring machine was set at an angle of 45 ° from the longitudinal direction of the sleeve and molten metal was poured by rotating the ladle from horizontal to vertical. Figure 1 shows the outline of the target die casting machine. The diameter of the sleeve was 60 mm and the length from the front edge of the plunger tip to the side of the sprue core was 220 mm. Therefore, the plunger moved 200 mm taking into consideration the thickness of the biscuit. In the mold, the runner section and the product section were mutually-independent insert dies. Therefore, we can set any combination of the inner runner die and the inner product die. In this study, we use a triple runner inner die and a two-cavity inner die. The plunger lubricant was a powder lubricant, which is effective for estimating air entrapment at the time of injection because the quantity of gas that rises from it is less than that emitted by liquid lubricant.

Table 1 Relationship between setting and actual measured values of shot time lag

Setting value of shot time lag [s]	0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8
Actual measured value of shot time lag [s]	0.99	1.07	1.29	1.50	1.70	1.87	2.09	2.28	2.44	2.68

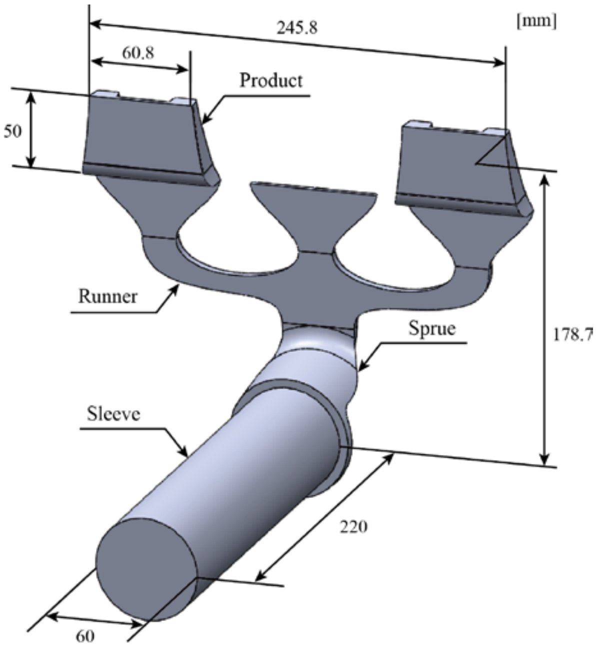

Fig. 1. Outline drawing of target die casting machine.

3. Verification experiment

3.1 Practical experiment

Because molten metal fluctuates when poured, molten metal behavior at the time of injection changes at the beginning of injection. Therefore, we examined whether casting defects increase or decrease due to molten metal fluctuation at the time of pouring. Pouring was carried out at a constant speed of 0.667 rad/s by a ladle, and the injection velocity of the plunger was constant at 0.2 m/s. We experimented with 10 shot time lag conditions from 0 s to 1.8 s at 0.2 s intervals. Table 1 shows the relationship between the setting value and the actual measured value of shot time lag. We obtained 3 samples under each condition, yielding a total of 30 samples.

Each sample obtained in the practical experiment was divided between the product and other parts, and its volume and mass were measured by an electronic densimeter. The volume of the blowholes per mass of one product is described by

$$v = \frac{V}{M} - \frac{1}{\rho} \tag{1}$$

where the product volume and mass in the atmosphere are V and M respectively, and the density of material is ρ. For the purposes of the present study, v indicates specific air volume and we use the above equation to evaluate the volume of a blowhole. Density of material was 2.74 g/cm^3 for all samples.

Figure 2 shows the average specific air volume of the product for each experimental condition. The experimental results confirm that changing the shot time lag has an impact on the volume of blowholes in a product because the specific air volume changes periodically.

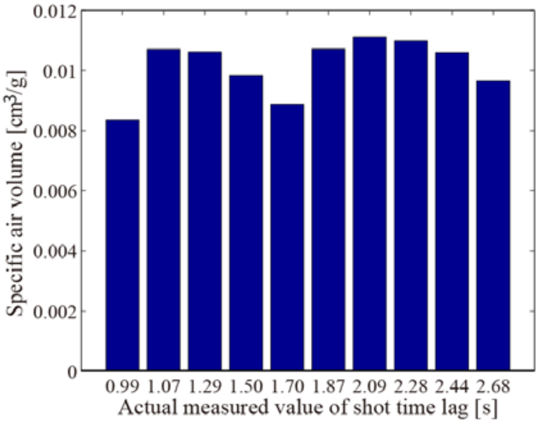

Fig. 2. Experimental result.

3.2 Die casting simulator and evaluation of air entrapment

We constructed a die casting simulator that reconstructs the pouring and injection processes and evaluated air entrapment under the various experimental conditions. Figure 3 is an outline drawing of the die casting simulator. This simulator has a range among a sleeve, a sprue and a runner, and defines the analysis area using two mesh blocks with a cell size of 2.5 mm for the XYZ directions.

In the simulation, the fluid was aluminum alloy ADC12, whose properties are shown in Table 2. In the actual casting, the casting weight was 0.695 kg and the volume of fluid was approximately 280 cm^3. In the simulation, however, fluid volume decreased because of a calculation error while pouring into the sleeve. Therefore, the fluid volume set into the ladle was 285 cm^3 taking the calculation error into consideration. The fluid volume after pouring was decreased by the calculation error and became approximately 280 cm^3.

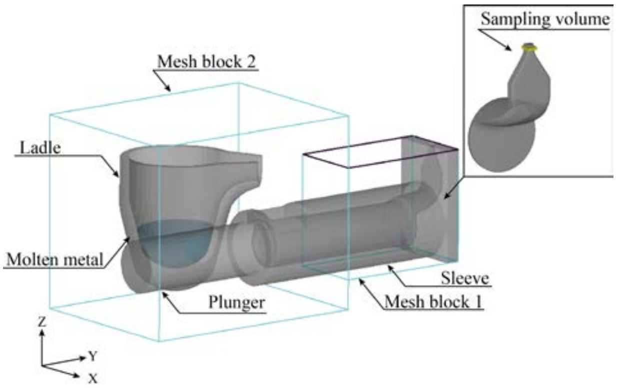

Fig. 3. Outline drawing of die casting simulator.

Table 2 Fluid properties of ADC12

Density	2471.6 kg/m^3
Viscosity	0.00125 P·s
Surface tension coefficient	0.9 N/s
Contact angle	90 °

We evaluated air entrapment using the above simulator. The evaluation value was defined as the volume of entrapped air, specifically, the air volume in the sleeve at the time when the sampling volume is filled by fluid.This can be defined as

$$J_1 = V_{\text{air}} = \left(\frac{1-\alpha}{\alpha}\right) V_{\text{fluid}}\left(t_f\right) \qquad (2)$$

where V_{air} and V_{fluid} are the air and fluid volumes in the analysis area, respectively, and α indicates the ratio of V_{liquid} in the spatial volume in which fluid may physically exist.

Figure 4 shws the analysis results, in which the evaluation value as well as the experimental results move periodically at 8 s intervals. The peak of the volume of the entrapped air coincides with the peak of the specific air volume in the experiment. In the following section, therefore, we use J_1 as one of the objective functions for injection velocity optimization.

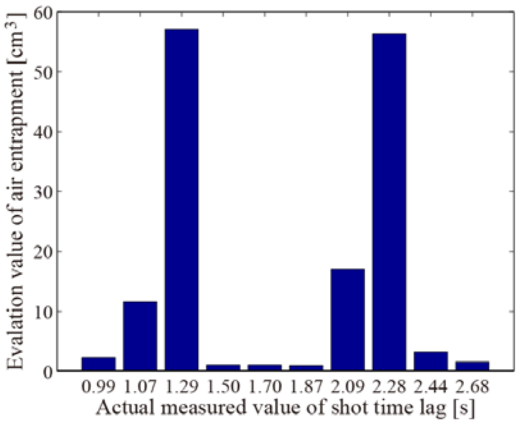

Fig. 4. Analysis results under the different experimental conditions.

4. Injection velocity optimization

4.1 Design variables and formulation of optimization

In the above section, we confirmed that fluid fluctuation at the time of pouring has the impact on a volume of blowhole in a product. Therefore, we design an injection velocity input considering the pouring of molten metal and the shot time lag. Fig. 5 shows the relation a velocity switching position and an injection velocity. Design variables for optimization are 6 in total: velocity switching position x_1 and x_2, a velocity at a velocity switching position v_1, v_2 and v_3 and a shot time lag t_{shot}. Velocity switching position to high speed x_3 is 15.2 cm.

The objective functions for the optimization are an entrapped air volume and a completion time of injection. An entrapped air volume is defined as Eq. (2). A completion time of injection is defined as

$$J_2 = t_5 = \sum_{i=1}^{5} \frac{2\left(x_i - x_{i-1}\right)}{v_i + v_{i+1}} + t_{\text{shot}} \qquad (3)$$

where $x_0 = v_0 = 0$.

We consider the optimization problem is to minimize the objective functions, and it is defined as

$$\begin{aligned} &\text{minimize} && J_1, J_2 \\ &\text{subject to} && x_1 \le x_2 \le x_3 = 0.152\text{m} \\ &&& v_1, v_2, v_3 \le 0.3\text{m/s} \\ &&& 1.0 \le t_{\text{shot}} \le 3\text{s} \end{aligned} \qquad (4)$$

The injection velocity of a die casting machine can be set to up to several dozen m/s. In the present study, however, we set an upper limit of 0.3 m/s as the injection velocity, which ensures that there will be no wave collapse at the time of injection.

In the present study, we used sequential approximate optimization, that is, a kind of response surface method. A response surface method is an efficient searching method that generates an approximate function of objective functions by complementing certain sampling points. Therefore, it can reduce sampling points as compared to heuristic optimization (e.g. genetic algorithm) and it has been used in the case of large scale simulation (e.g., CFD analysis) [4,5].

For the response surface, the approximate function is a quadratic polynomial and we then sought an optimal point on the approximate function using multi-objective genetic algorithm NSGA-II.

For injection on an actual die casting machine, it is difficult to match the designed injection input exactly because of the characteristics of the machine. Therefore, we computed the evaluation value J_1 on shot time lag t_{shot} and t_{shot} ±0.1 s and used the average of three values as evaluation value J_1.

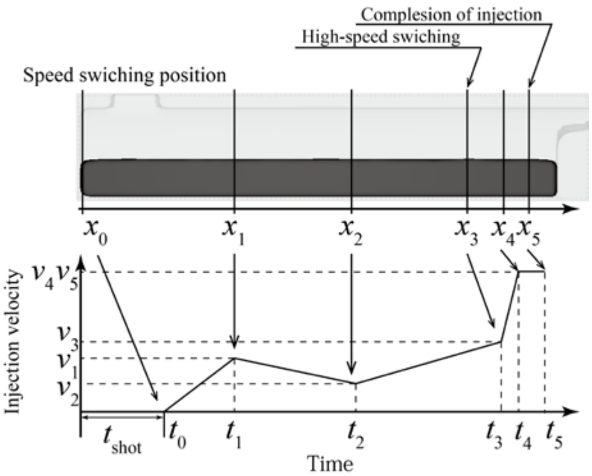

Fig. 5. Velocity curve of die casting plunger.

4.2 Optimization result

We used an Intel Core i7-2600K 3.4 GHz computer and performed 4 simulations in parallel. The time required for the optimization was approximately 23 hours.

Figure 6 shows the distribution of two evaluation values, J_1 and J_2, for 373 individuals simulated in the process of optimization. We selected the optimal solution (indicated by the arrow in the figure) as the optimal injection velocity input. Table 3 shows the variables and evaluation values of this optimal solution. In addition, Fig. 7 shows the waves of the derived injection velocity input and Fig. 8 shows its fluid behavior.

The derived injection velocity input is 1.0 s of shot time lag and the wave shows that the plunger injection accelerates gradually from x_1 to x_3. The fluid behavior indicates that pouring is complete at 2.8 s and 0.5 s from pouring injection starts and is completed without air entrapment. Since a molten metal wave caused during pouring exists close to the plunger, however, injection completed without the wave caused in pouring does not cross wave during injection, and injection is then completed successfully without perturbations in fluid level.

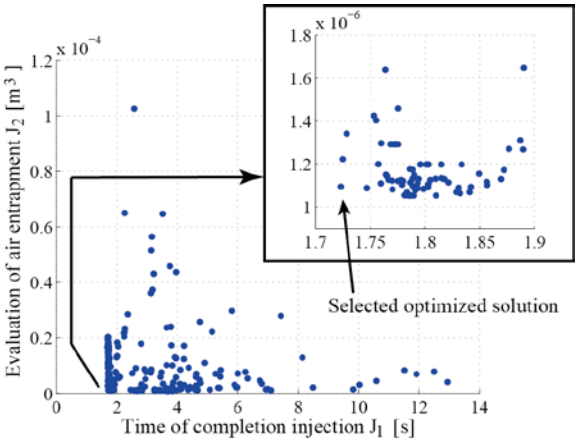

Fig. 6 Distribution chart of all the analyzed individuals

Table 1 Design variables and evaluation values of the optimized solution

x_1 [m]	x_2 [m]	v_1 [m/s]	v_2 [m/s]	v_3 [m/s]	t_{shot} [s]
0.01	0.10	0.21	0.30	0.30	1.0
J_1 [m^3]			J_2 [s]		
1.094×10^{-9}			1.723		

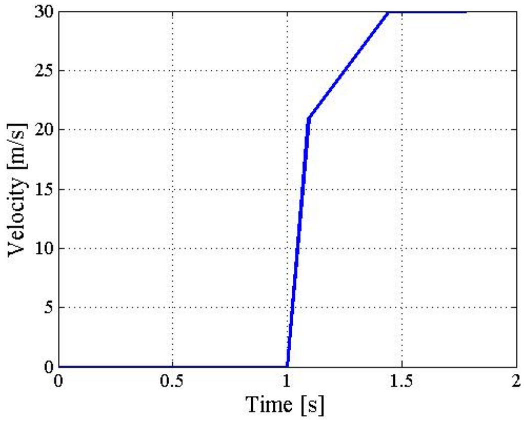

Fig. 7. Optimized injection velocity input.

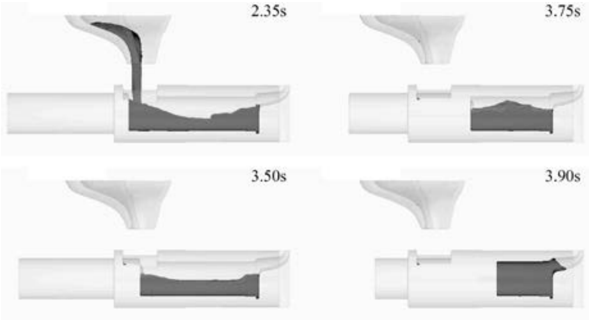

Fig. 8. Fluid behavior of the simulation with the optimized input.

5. Conclusion

In the present study, we examined the effect of the ruffle of molten metal that occurs during pouring on the quality of products. Our results show that changing the injection timing (shot time lag) has an impact on the volume of blowholes in the product. We also reconstructed the experimental conditions using a CFD simulator, and confirmed the fluid behavior. We proposed an evaluation method to evaluate blowholes in a simulator. We then designed a control input for plunger injection taking into consideration the pouring of molten metal and the waiting time. Further experiments with a die casting machine are necessary to test the effectiveness of this method.

6. References

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