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WAVE BEHAVIOR CAUSED BY LADLE POURING AND PLUNGER ADVANCING IN ALUMINUM ALLOY DIE CASTING USING PARTICLES-BASED SPH METHOD

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Abstract. Casting CAE software determines the operating conditions of ladle pouring and plunger advancing and prevents defects in aluminum alloy die casting. Quick operations of the ladle pouring and plunger advancing lead to disturbance of the molten metal flow and increase the risk of air entrapment. Conversely, if these operations are performed slowly, the temperature of the molten metal drops, and the risk of cold flake formation increases. Furthermore, since an oxide film exists on the surface of molten aluminum alloy and flows differently from water, it is necessary to perform simulations considering the oxide film.

In conventional casting CAE simulation, the flow behavior by the plunger advancing is often simulated from a state in which the molten metal is stationary in the sleeve. In this study, we numerically analyze wave behavior caused by ladle pouring and plunger advancing processes. One is the superimposed ones of wave behavior when ladle pouring and plunger advance processes are simulated separately. The other is the wave behavior when simulated as a series of processes. The casting analysis software “COLMINA CAE” by the particle-based SPH method, which is considered the oxide film of molten aluminum alloy, is used to analyze the wave behaviors. Further, they have verified the wave behavior through visualization experiments.

Comparing the simulated wave height and velocity, which shows the wave motion generated when the plunger advances from the stationary state of the molten metal in the sleeve is different from the wave motion in a series of processes, suggesting the need for simulation of a series of processes. These trends of wave behavior obtained in the simulation are similar to that of the actual phenomenon. Therefore, the present simulation method can accurately estimate the ladle pouring process and plunger advancing process.

Keywords: Die casting, Aluminum alloy, Ladle pouring, plunger advance, Wave behavior, Oxide films

1 INTRODUCTION

Die casting is a casting method that involves injecting molten metal into a precision mold at high speed and high pressure. This enables the mass production with excellent dimensional accuracy and surface finish. The main processes are ladle pouring, plunger advancing, and cavity filling, as shown in Figure 1. Molten metal is poured into the sleeve by tilting the ladle, and then it is filled into the cavity by being pushed out by the plunger. At this time, the formation of cold flakes and the entrapment of air can cause defects [1-7]. The casting CAE is highly effective for setting appropriate conditions [8]. However, the die casting process involves a moving boundary problem, and accurately capturing the free surface is necessary to understand air entrapment behavior. The particle-based method is effective for these aspects [9]. Furthermore, an oxide film exists on the surface of molten aluminum alloy, necessitating simulations that account for this.

From a computational cost perspective, calculations often start with the molten metal stationary within the sleeve, ignoring the waves generated during ladle pouring. However, the relationship between the wave generated by the ladle tilting and those produced during plunger advancing remains insufficiently investigated due to the difficulty of experimental investigation. In this study, the wave behaviors, such as ladle pouring, plunger advancing, and those combinations, are investigated using "COLMINA CAE" [10-12]. Further, by simulating a series of processes from ladle pouring to plunger advancing, shot time lag can be examined. Therefore, to clarify the effect of shot time lag differences on the wave during plunger advancing, both experiments and simulations were conducted.

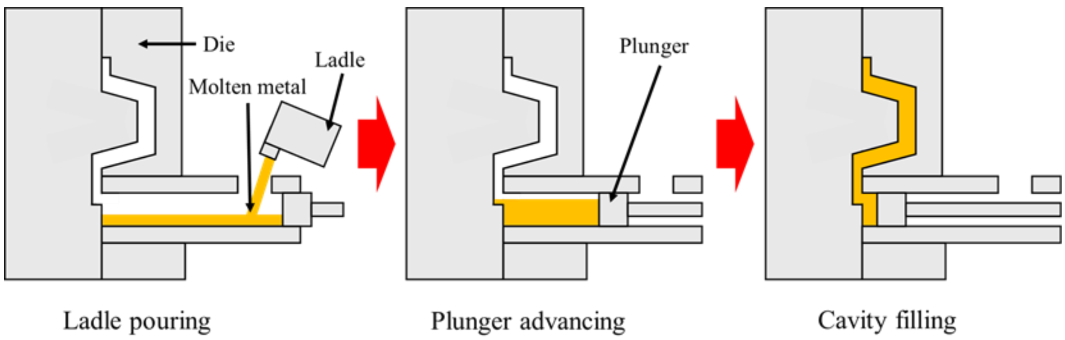


Figure 1: Overview of the die casting process.

2 EFFECTS OF LADLE POURING ON WAVES DURING PLUNGER ADVANCING

2.1 Analysis model and calculation conditions

Figure 2 shows an overview of the analysis model for the visualization experimental apparatus [8]. The analysis model consists of a ladle, sleeve, plunger, plunger-side brick, and virtual cavity. The ladle height is 147mm from the sleeve. The calculation conditions are shown in Table 1. The simulation uses particle-based SPH software "COLMINA CAE". Aluminum alloy JIS-ADC12 is used as the test material. This software can take into consideration the oxide film on molten aluminum alloy. The particle size is set to 1.0mm, and the radius of influence is set to three times the particle size. COLMINA CAE uses the explicit weakly compressible SPH method. So, the sonic speed is the tuning parameter, then it is 10 times the maximum speed observed in the simulation. Table 2 shows the physical properties of JIS-ADC12 aluminum alloys. When the mass of molten metal inside the sleeve is 300g, the sleeve filling rate is 36.6%. The ladle is set at 300°C to prevent a rapid temperature drop of the molten metal. These conditions are almost the same as those in the literature [13,14].

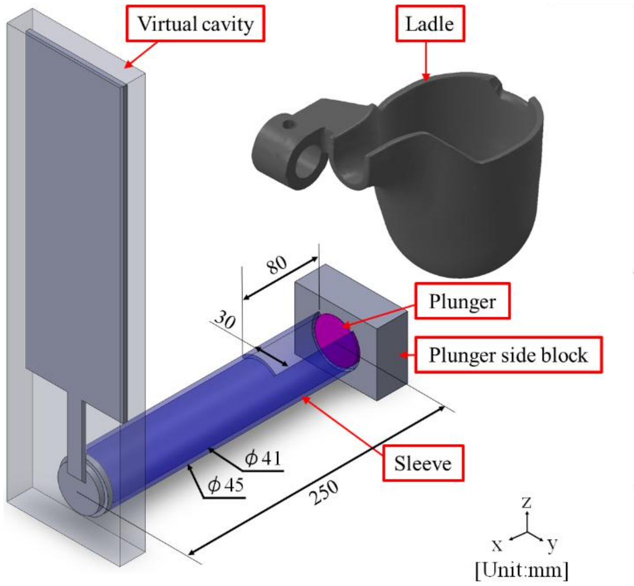


Figure 2: Analysis model.

Table 1: Calculation conditions.

SPH software	COLMINA CAE
Test material	Aluminum Alloy, JIS-ADC12
Amount mass of materials	300g
Pouring temperature	700°C
Particle size	1.0mm
Total number of particles	1,820,332
Influence radius	3.0mm
Parameter for Sonic Speed	20m/s

Table 2: Physical properties of aluminum alloy of JIS-ADC12.

Phase	Liquid phase	Solid phase
Density	2480 kg/m^3	2700 kg/m^3
Specific heat	1080 J/(K·kg)	960 J/(K·kg)
Thermal conductivity	96 W/(K·m)	237 W/(K·m)
Latent heat	396800 J/kg	-
Viscosity	2.728×10^{-3} Pa·s	-
Surface tension	0.886 N/m	-

Table 3 shows the conditions for ladle pouring and plunger advancing. The ladle tilting speed is 0.46 rad/s, and the shot time lag(the time from ladle pouring completion to plunger advance start) is 0s. The plunger advance speed is set to 221mm/s. Table 4 shows the oxide film parameters of COLMINA CAE[7].

Table 3: Conditions for Ladle pouring and Plunger advancing.

Ladle tilting speed	0.46rad/s
Shot time lag	0s
Plunger advancing speed	221mm/s

Table 4: Oxide film parameters in COLMINA CAE.

Thickness of oxide film	0.25μm
Viscosity of oxide film	27280Pa・s
Breakdown pressure of oxide film	2000Pa
Regeneration time of oxide film	0.016s

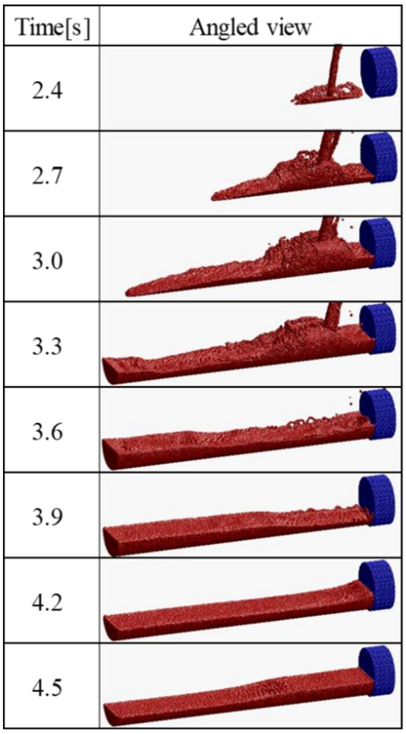


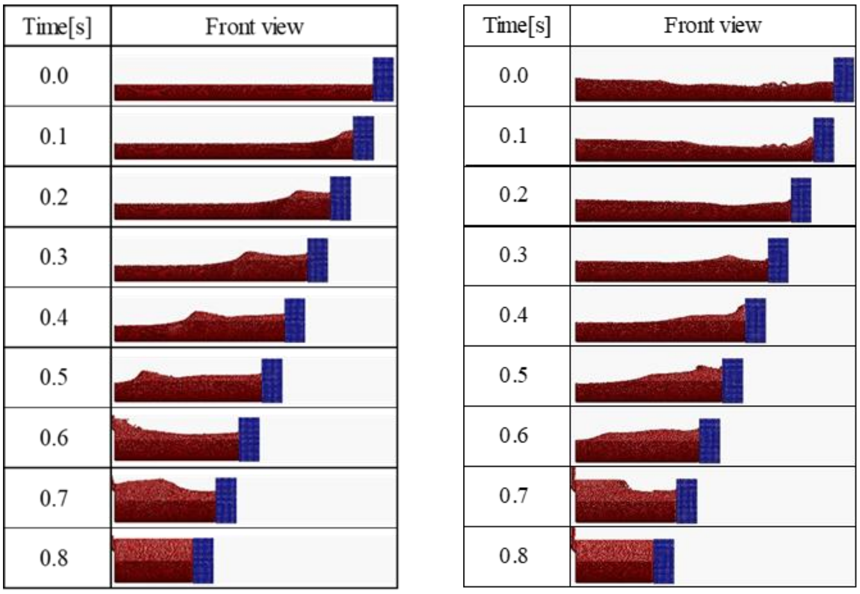
Figure 3: Wave behavior generated by ladle tilting speed of 0.46 rad/s.

2.2 Waves generated by ladle pouring

Figure 3 shows the wave behavior during and after pouring when the ladle tilting speed is 0.46rad/s. Time is measured from the start of ladle tilting. The flow front of molten metal contacts around 2.4s from ladle tilting initiation, causing a rapid rise. The molten metal surface subsequently decreases over time. Furthermore, as pouring progresses, the molten metal front advances toward the biscuit side, colliding with the biscuit wall after 3.0s. Subsequently, a wave heading toward the plunger can be observed upon completion of pouring. Afterwards, the wave continues to oscillate back and forth within the sleeve.

2.3 Comparison of wave behaviors during plunger advancing

Figure 4 compares the wave behaviors at a plunger advancing velocity of 221mm/s, differing from the initial states. One is the hydrostatic state, and the other is the state after ladle tilting. Time indicates from the start of plunger advance at 0s. When the plunger advances from a hydrostatic state, the molten metal surface rises immediately upon initiation and then transitions to a smooth shape. When the wave collides with the biscuit wall at 0.6s, the surface rises again. In the case of plunger advancing that starts from the state after ladle tilting, the wave generated by ladle tilting collides with the plunger at 0.4s, causing the molten metal surface in front of the plunger to rise. From these different wave behaviors, it is clear that the wave generated by ladle tilting influences the wave generated by plunger advancing, it cannot be ignored.



(a) Hydrostatic Condition (b) After Ladle Pouring

Figure 4: Wave behavior during plunger advancing velocity of 221 mm/s.

2.4 Evaluation of wave height

Waves possess the properties of superposition and independence. It may be possible to reproduce the wave generated during plunger advancing after ladle tilting in by superimposing the wave generated during ladle tilting with the wave generated by the plunger advancing from a hydrostatic state. Namely, it may be that the wave height of Figure 4(b) equals the sum of the wave heights of Figure 3 and Figure 4(a). For this verification, the wave height, which is the distance from the sleeve bottom to the wave surface of the molten metal, was measured at a total of 11 measurement positions as shown in Figure 5.

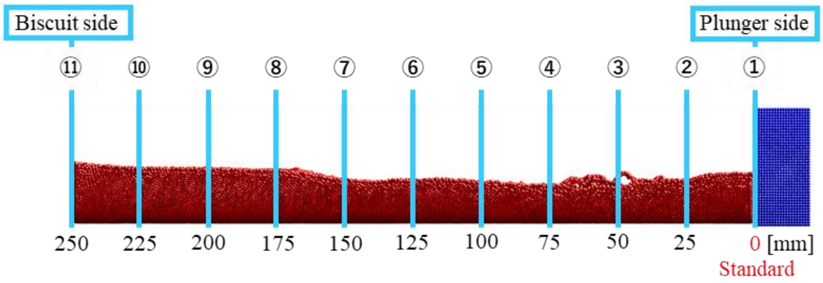


Figure 5: Measurement point of wave height.

The measurement results are shown in Figures 6 and 7. As mentioned above, the finishing time of pouring is 3.6s at a ladle tilting speed of 0.46rad/s. The wave height generated by ladle tilting is shown in Figure 6; the value of time 0 on the horizontal axis indicates the finishing time of pouring. Namely, it means the same as the start time of plunger advancing. Figure 7 shows the wave height during plunger advancing from the hydrostatic state.

For the wave generated by ladle tilting, the molten metal surface at the 250mm measurement point is highest at 0s, the finishing time of pouring. Subsequently, the wave height decreases and approaches asymptotically the wave height of the hydrostatic state, 15.7mm, at approximately 3.2s.

In the wave generated by the plunger advancing from the hydrostatic state, the wave propagating toward the biscuit side forms in front of the plunger. Consequently, the wave surface rising phenomena sequentially occur from the measurement point 25mm closest to the plunger, following the wave's propagation. The wave collides again with the biscuit wall at approximately 0.65s, and the propagating direction of the wave reverses. The wave surface sequentially rises from the measurement point closest to the biscuit at 250mm. Subsequently, at approximately 0.98s, the wave collides with the plunger and reaches the top of the sleeve at a height of 41mm.

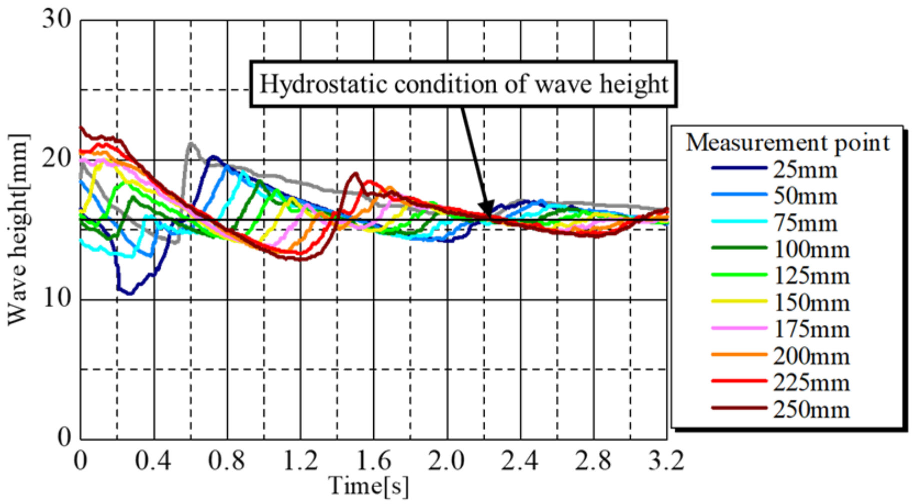


Figure 6: Wave height of molten metal in the sleeve after ladle pouring.

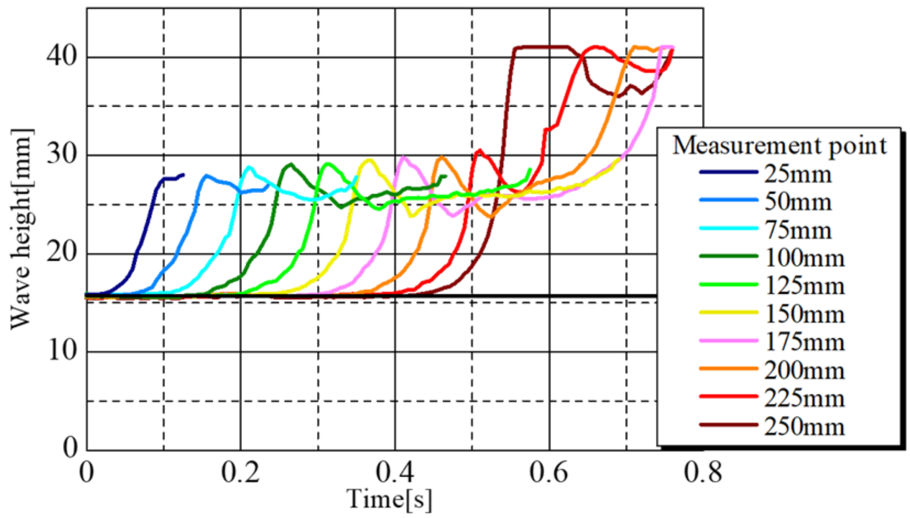


Figure 7: Wave height of molten metal during the plunger advancing from the hydrostatic state.

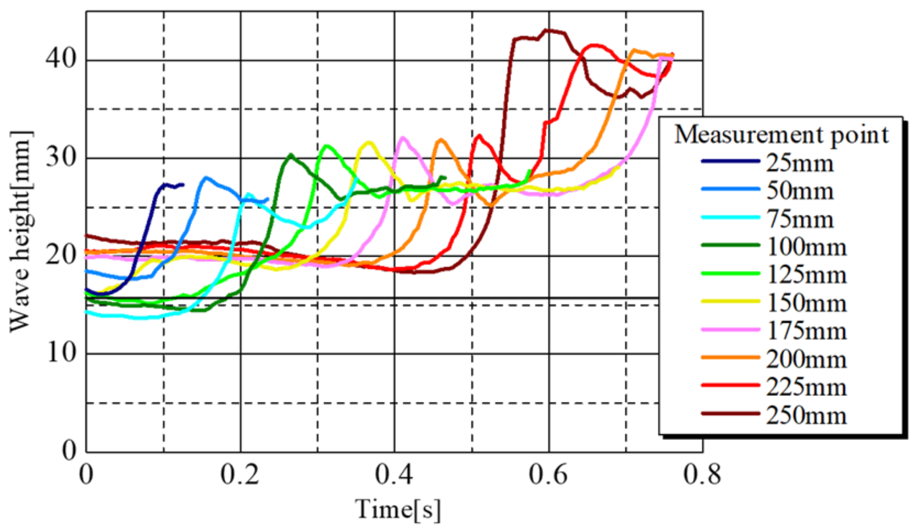


Figure 8: Wave height of the superimposed wave.

2.5 Height of the superimposed wave

The wave displacement from the hydrostatic state is calculated by subtracting the hydrostatic state height of 15.7mm from the measured wave height in Figure 7. Then, the height of the superimposed wave was obtained by adding the wave height generated by ladle tilting in Figure 6 and the displacement. The height of the superimposed wave is shown in Figure 8. On the other hand, the sequential calculation of the ladle pouring and plunger advancing is executed to compare the wave behavior, and the result of the wave height is shown in Figure 9.

In the sequential simulation, the wave generated by the ladle tilting collides with the plunger at approximately 0.45s, causing the wave surface in front of the plunger to rise. However, this behavior is not observed in the superimposed wave; the wave height remains constant until the wave generated by the plunger advance collides with the biscuit wall. This difference in wave height behavior is a natural result, given that the wave shapes at time 0s in Figure 4 are different. Further, comparing the peak values at the measurement position closest to the plunger (25mm), a difference in the wave height generated by the plunger advancing is observed. Consequently, the time at which this wave collides with the biscuit wall also differs, indicating a difference in wave velocity.

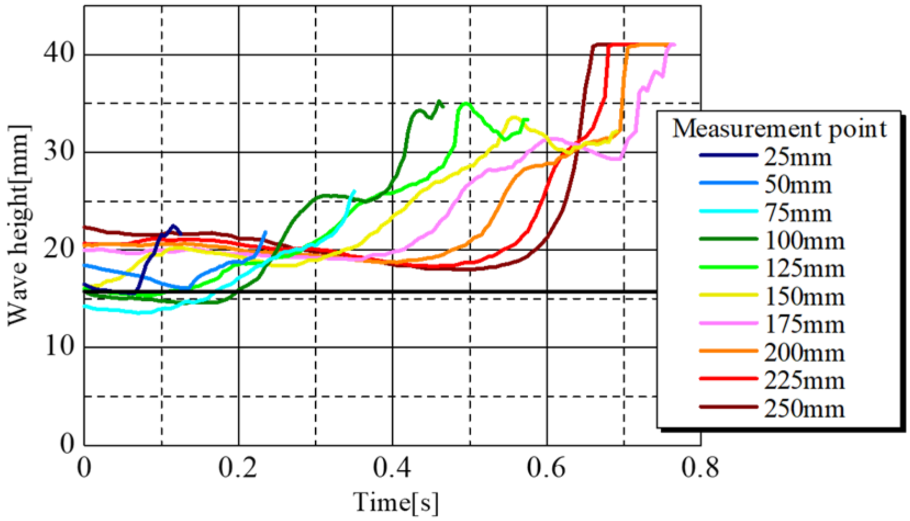


Figure 9: Wave height when simulated as a series of processes.

3 THE EFFECT OF SHOT TIME LAG ON WAVE

3.1 Condition for shot time lag

F. Itakura et. al.[14] carried out the experiments and simulation varying with the plunger speed. They investigated the effect of differences in plunger advancing speed on wave behavior. Then, the ladle tilting speed and the shot time lag conditions were constant.

In this research, we focused on how the effect of shot time lag differences on the wave during plunger advancing. Shot time lag refers to the interval between the finishing time of ladle pouring and the beginning time of plunger advancing. Controlling the shot time lag alters the wave position and wave height during plunger advancing, thereby changing the injection behavior through the ingate to the cavity.

Table 5 shows the experimental and calculation conditions for ladle pouring and plunger advancing. The investigation of wave behavior is executed under two conditions of the shot time lag. One is 0s (3.6s from tilting start), where plunger advancing begins as soon as the ladle tilting is finished. The other is 0.6s (4.2s from tilting start), where the plunger advancing begins when the wave propagates toward the biscuit. Other conditions remain the same as in the previous section. These conditions were examined through simulation and experiment.

Table 5: Experimental and calculation conditions for ladel pouring and plunger advancing.

Ladle tilting speed	0.46rad/s
Shot time lag	0, 0.6s
Plunger advancing speed	221mm/s

3.2 Comparison of experimental and analytical results

Figures 10 and 11 show the flow behavior during plunger advancing at shot time lags of 0s and 0.6s. Figure 12 indicates the maximum liquid level height within the sleeve during ladle tilting and plunger advancing. These figures are expressed with the start of ladle tilting set as 0s.

From the experimental results of Figure 10, in the case of a shot time lag of 0s, the molten metal surface rises immediately as soon as the plunger advances. At that time, the high wave generated by ladle tilting is located at the biscuit side, and the wave height in front of the plunger is lower. At 3.9s, one peak of the wave is observed, and it reaches a maximum value of 35mm at 4.1s. Subsequently, the wave propagates toward the biscuit, with the molten metal contacting the sleeve top surface at 41 mm around 4.3 s. The analysis also shows the same wave behavior of rising immediately and suppressing the wave height. Further, neither the experiment nor the analysis observed wave breaking under this condition.

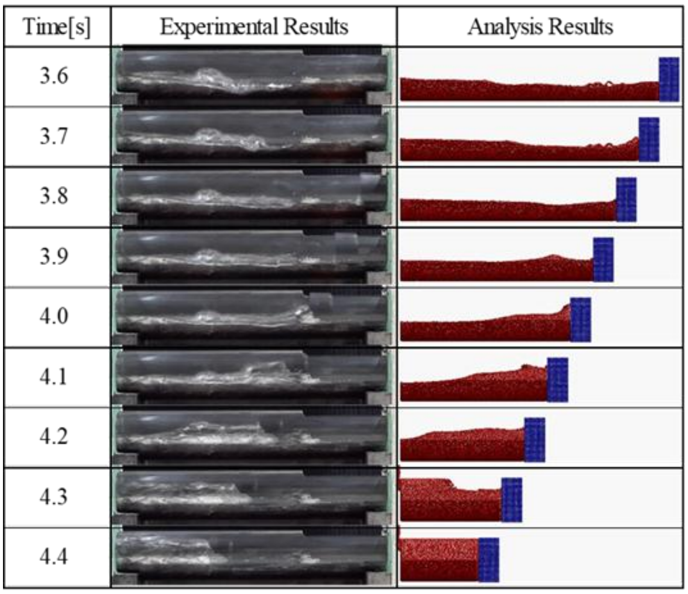


Figure 10: Wave behavior during plunger advancing at a shot time lag of 0s

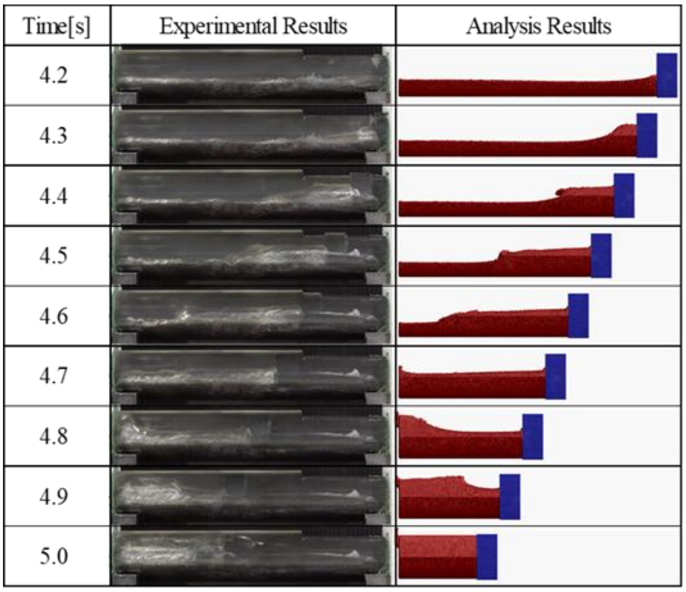


Figure 11: Wave behavior during plunger advancing at a shot time lag of 0.6s

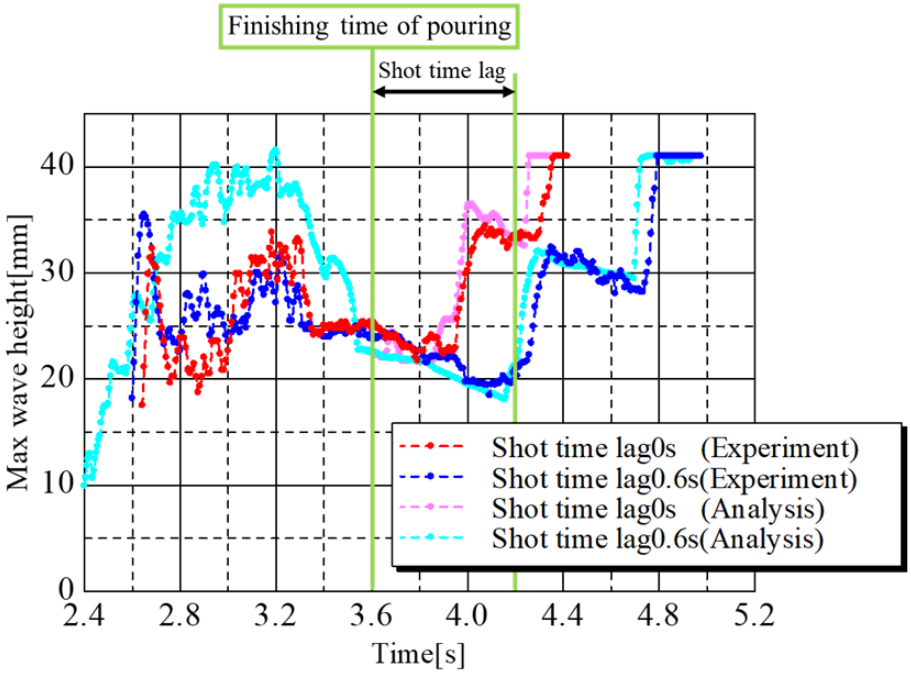


Figure 12: Maximum wave height when varying the shot time lag

In the case of a shot time lag of 0.6s, the wave height in front of the plunger at the beginning of the plunger advancing is high. The wave height becomes high as the plunger advances. Then, a breaking wave, which the wave collapses onto the front surface, occurs at approximately 4.5s. In this condition, too, the analysis shows the same wave behavior in the experiments. These figures are shown to have good validation results. This demonstrates the effectiveness of the oxide film model in COLMINA CAE.

Observing the difference between the two figures, it can be seen that the difference in shot time lag, i.e., the wave height in front of the plunger tip when the plunger starts to advance forward, affects the flow behavior.

4 CONCLUSIONS

In the aluminum alloy die casting process, the wave behaviors such as ladle pouring, plunger advancing, and those combinations are investigated using particle-based software. The following results are obtained.

1) The superimposed wave, which combines the waves generated by ladle tilting and plunger advancing, does not match the wave behavior obtained by sequentially calculating the ladle tilting and plunger advancing. So, although it increases the computational cost, simulation of ladle tilting is necessary.
2) Even at the same plunger advancing speed, varying the shot time lag causes fluctuations in wave generation and propagation, altering the flow behavior.
3) The flow behavior obtained from the simulation is similar to that observed in experiments, demonstrating the effectiveness of simulations using COLMINA CAE.

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