Mold Filling Simulation for Predicting Gas Porosity

KIMATSUKA Akihiko : Manager, Production Technology Development Department, Production Engineering Center, Corporate Research & Development
KUROKI Yasunori : Doctor of Engineering, Manager, Materials Department, Research Laboratory, Corporate Research & Development

The process of mold filling requires consideration of the gas escape through the mold, gas vents and gas generation on the mold surface during mold filling. The pressure in the cavity increases due to compression of the gas by the melt, affecting the mold filling behavior. Further, the melt entraps gas or air in the die cavity. This paper presents a method to simulate mold filling while considering the backpressure and gas escape. The governing discrete equations for the momentum and mass conservation laws were derived by the DFDM (Direct-Finite-Difference-Method). Simulated mold filling patterns agreed rather well with the results directly observed by X-ray apparatus.

1. Introduction

In mold filling of the casting process, such casting defects as miss run, cold shut, gas and oxide film entrapment, and shrinkage often occur. During pouring, gas in the mold is compressed by the melt and discharged outside through the sand mold in sand mold casting or through the vent in metallic mold casting such as die-cast. If the casting method is not proper, such gas defects as miss run due to back pressure of the gas and gas entrapment occur. In the sand mold casting, gas generation from the binder and moisture also cause gas defects. To eliminate these defects, casting methods are investigated through experience and experiments, but much development cost and a long development period are required, and recently, therefore, simulation has been increasingly used. For this reason, many studies on mold filling and solidification analysis in the casting process have been conducted,[(1)-(9)] and some commercial software has been sold on the market and utilized as a tool for predicting defects and investigating casting methods by many casting companies. But in many conventional mold filling simulations do not consider the effect of back pressure in the cavity, and the consideration of the back pressure has not been applied for sand mold casting, though in some cases it has been applied for die-casting [(10), (11)] and sand core. [(12)]

In this study, therefore, we have developed a simulation code to predict gas entrapment defects considering the effect of back pressure, sand mold, and gas escape through the sand mold and vent. We applied the developed code to several cases of melt flow, investigated the validity of this analysis method by comparing by direct observation with X-ray, and applied it to actual products, and report the results.

2. Simulation methods

2.1 Modeling of melt flow

For the melt flow, the governing equation of incompressible fluid is made discrete by the Direct Finite Difference method.[(6), (7), (13)] For the momentum conservation area, staggered elements were used. The direct finite difference formula of the momentum conservation law of the melt is as follows.

$$(\rho V)_{IS} \frac{(u_{IS}^{t+\Delta t} - u_{IS}^{t})}{\Delta t} = M_C + M_v + M_g + M_P + M_d \quad \cdots (1)$$

ρ	Density
V	Volume
u_{IS}	Velocity
t	Time
Δt	Time step
Subscript IS	Number of velocity on nodal region
M_C	Convection term
M_v	Viscosity term
M_g	Gravity term
M_p	Pressure term
M_d	Darcy's term

The mass conservation area of the melt is made an element within the nodal region, and the mass conservation law is expressed by the following formula.

$$\sum_j \vec{\beta}_s S_{ij} u_{IS}^{t+\Delta t} \boldsymbol{n}_{ij} = 0 \quad \cdots (2)$$

$\vec{\beta}_s$	Melt filling ratio of element surface
Subscript i, j	Element numbers on both sides of surface IS
S_{ij}	Area of surface between i and j
$\boldsymbol{n}_{ij}$	Outward normal vector

In this analysis, the free surface [8] is accurately calculated by using 3 parameters, fractional volume of fluid β_v , melt filling ratio of element surface β_s , and dimensionless distance β_d.

2.2 Modeling of gas in cavity and mold

Figure 1 shows gas being discharged from the cavity (when melt is filled) mold filling sequence in the sand mold.

As to the gas in the cavity and sand mold, the following assumptions are made.

(1) Gas flow in the cavity is ignored.
(2) The gas in the cavity is an ideal one.
(3) The pressure, density, and temperature in the cavity are constant for each gas group.
(4) Gas flow in the sand mold is Darcy's flow.

Therefore, the gas mass conservation in the cavity is expressed by the following formula.

$$\frac{\rho_{ig}^{t+\Delta t} V_{ig}^{t+\Delta t} - \rho_{ig}^{t} V_{ig}^{t}}{\Delta t} = -\sum_j (\boldsymbol{n}_{ij} S_{ij} u_{c/m}^{t+\Delta t} \vec{\rho}_{ig}^{\,t}) \quad \cdots\cdots (3)$$

ρ_{ig}	Gas density
V_{ig}	Gas volume
$\vec{\rho}_{ig}$	Density of gas
$u_{c/m}$	Gas flow velocity at mold-cavity interface
Subscript ig	gas group number

The gas density is expressed by the following formula.

$$\rho_{ig}^{t+\Delta t} = \frac{M}{RT_{ig}} P_{ig}^{t+\Delta t} \quad \cdots\cdots (4)$$

M	Number of molecules of gas
R	Gas constant
T_{ig}	Gas temperature
P_{ig}	Gas pressure

The mass conservation in the sand mold is expressed by the following formula.

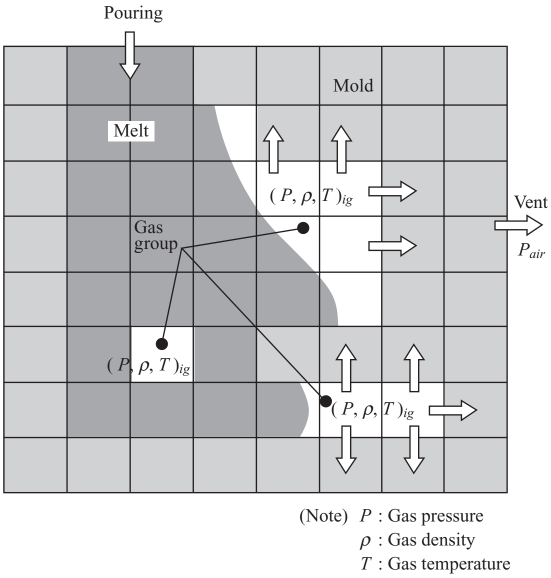

Fig. 1 Gas group in mold cavity

$$\frac{\rho_i^{t+\Delta t} - \rho_i^{t}}{\Delta t} V_i \varepsilon = -\sum_j (\boldsymbol{n}_{ij} S_{ij} u_{ISm}^{t+\Delta t} \vec{\rho}_{ij}^{\,t}) + V_i Q_m (T_m) \quad \cdots\cdots (5)$$

ρ	Gas density
ε	Void fraction of mold
$\vec{\rho}$	Density of gas
Q_m	Gas generation ratio
T_m	Mold temperature

Assuming that the gas flow in the sand mold is Darcy's flow.

$$u_{ISm}^{t+\Delta t} = \frac{P_i^{t+\Delta t} - P_j^{t+\Delta t}}{\mu R_T} \quad \cdots\cdots (6)$$

$$R_T = \frac{\Delta x}{K_m} + \frac{d_c}{K_c} \quad \cdots\cdots (7)$$

u_{ISm}	Gas flow velocity on mold surface ISm
P	Gas pressure
μ	Gas viscosity
Δx	Distance from surface ISm to element center
Subscript ISm	Mold surface number
K_m	Permeability of sand mold
d_c	Thickness of coating
K_c	Permeability of coating

When the surface ISm is on the outer surface of the sand mold, P_i or P_j is replaced with external pressure (normally atmospheric pressure).

If the surface ISm is on the mold surface and is adjacent to non-filled element, P_i or P_j is replaced with back pressure P_g. By making $u_{c/m}$ the velocity of being discharged from the vent, with void fraction of mold $\varepsilon = 0$, it can also be applied for the metal mold casting.

2.3 Analysis flow chart

Figure 2 shows the calculation procedure. The back pressure was considered by making the gas in the cavity at time t the boundary condition when solving the Poisson equation of the melt pressure of time $t + \Delta t$.

2.4 Modeling of predicting gas defect

Of gas groups, a group without gas escape was defined as gas defect element (large gas entrapment defect). Gas groups smaller than the element size are replaced with markers and traced to predict very small gas defects. The algorithm of gas defect predicting procedure is shown below.

(1) A gas group surrounded by the melt is defined as a gas defect group.
  ① Sand mold casting: group not facing the mold
  ② Metal mold casting: group not facing vent, etc.
(2) If any gas defect group becomes smaller than the element size, one marker is generated at the element center.
(3) Very small gas entrapped is carried by the melt.
(4) If the marker is included again in the gas group, the marker is erased.

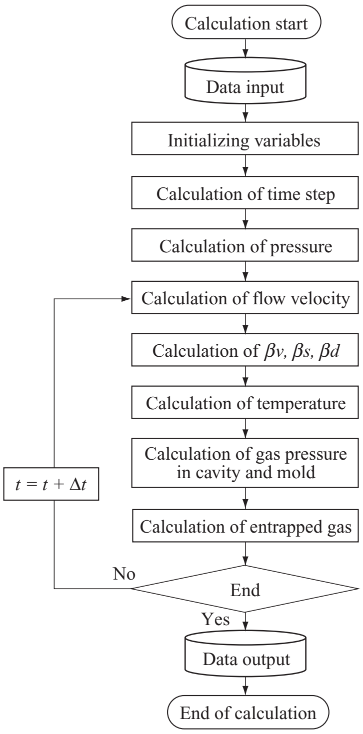

Fig. 2 Flow chart of calculation

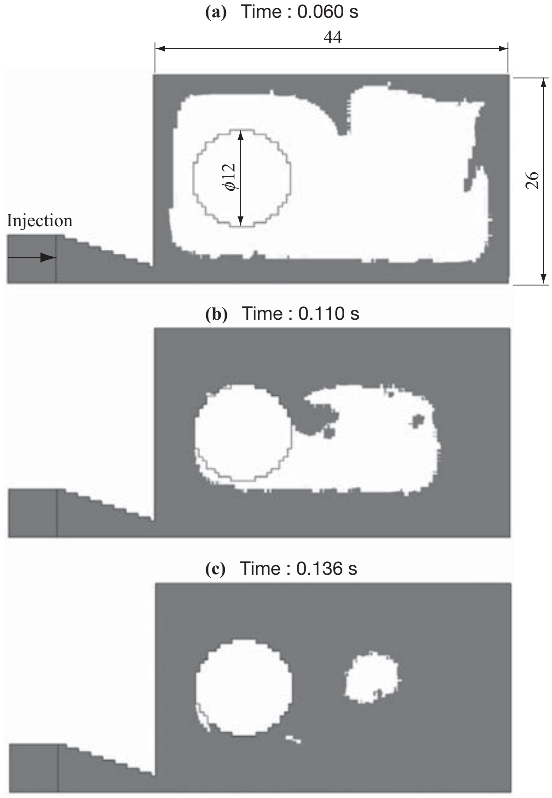

Fig. 3 Mold filling sequences (unit : mm)

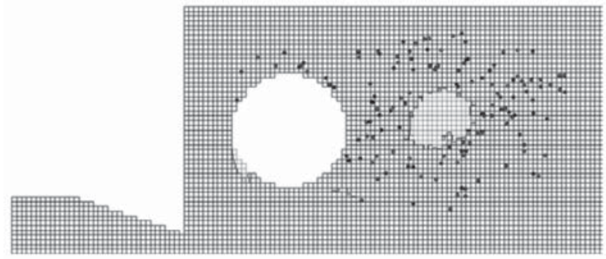

Fig. 4 Gas defect distribution

Collision between markers is ignored and adsorption when contact is made with the wall surface is not considered. Marker tracking makes it possible to predict very small gas entrapment defects that until now had been impossible.

3. Comparison with conventional reports

3.1 Comparison with calculation of Backer et al.

As a calculation example, we calculated using the simulation model of die-casting used by G. Backer et al.[10] This model has a round obstacle in a rectangular cavity and the melt is injected at 1m/s through the lower left gate. The properties of the melt are those of AC4C alloy. We assumed that gas from the cavity did not escape. **Figure 3** shows the simulation results of the mold filling sequence. The filling was done sequentially from the outer periphery of the cavity, and a large gas entrapment by the melt occurred near the cavity center at the final filling position. This result agrees well with that of G. Backer et al. **Figure 4** shows the simulation results of gas entrapment defects. The markers in the figure show the distribution of small gas defects of time : 0.136 s. With this model, it is predicted that many small gas defects will occur separately from large entrapment defects. Since these defects cannot be predicted by the conventional methods, this method is considered to be effective for predicting very small gas defects.

3.2 Comparison with experiments by Kanatani et al.

To validate the back pressure calculation, we conducted the calculation of squeeze casting. **Figure 5** shows the simulation results of mold filling sequence when water was injected into a rectangular cavity through the bottom gate at the velocity of 1.0 m/s constant. For the calculation, we used the grid of 53 × 100 and adopted no-slip condition for the wall surface.

One division is made in the thickness direction (thickness 10 mm), and the slip condition is adopted for the wall surface, thus making two-dimensional analysis. Two vents were arranged at the upper part of the cavity. **Figure 5-(a)** shows the results when the back pressure was not considered, and **-(b)** the results when the back pressure was considered, and at the inclined area of the cavity bottom, air is entrapped. When the back pressure is not considered, entrapped bubbles immediately disappear, but when it is considered, the entrapped bubbles are not discharged and remain to the last. The calculation results when the back pressure was considered agree well with the experimental results of Kanatani et al.[9] shown in **Fig. 6**, indicating that the effect of the back pressure is large when there is no gas escape.

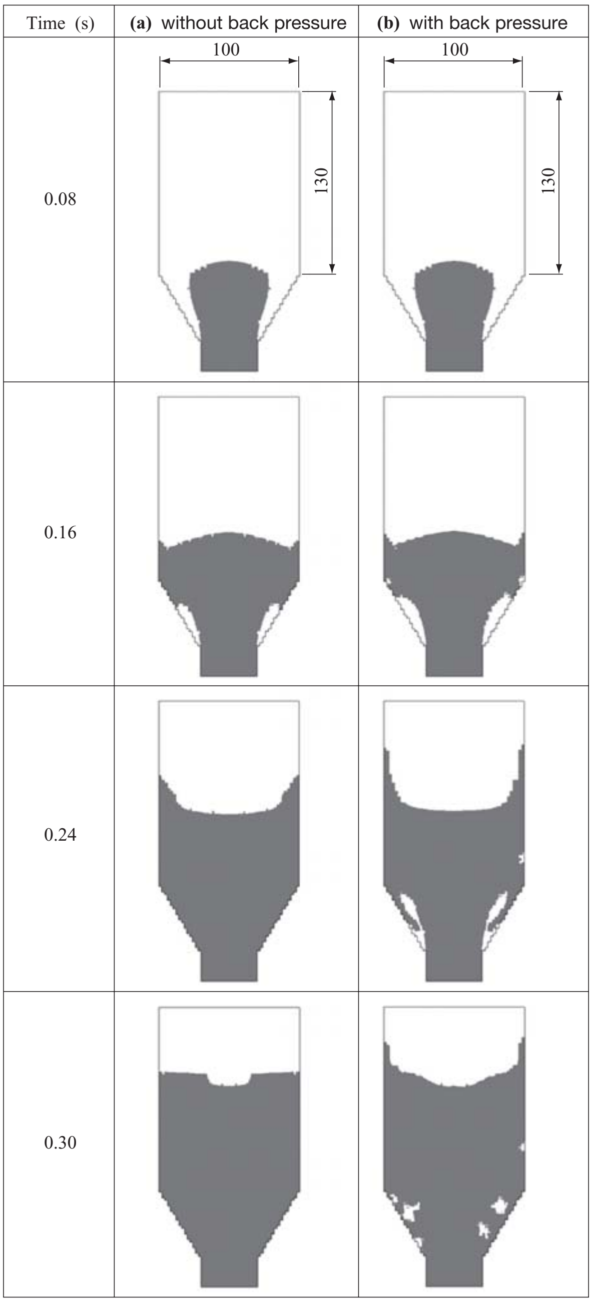

Fig. 5 Effect of backpressure on mold filling sequence

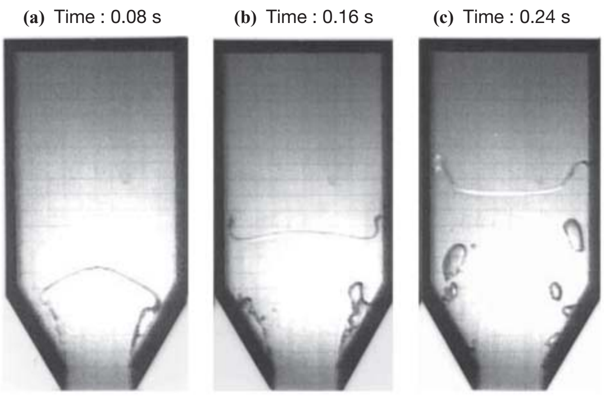

Fig. 6 Experimental mold filling sequence

4. Validation by comparison with melt flow observation with X-ray

4.1 Experiments

With the mold shape shown in **Fig. 7**, casting experiments were conducted, and the mold filling behavior was directly observed with X-ray apparatus. [14] For the experiments, fran mold and material FC250 were used. The specifications of the experimenting equipment are shown below.

X-ray tube voltage 0 - 225 kV
X-ray tube current 0 - 13 mA
Maximum output 3 kW
High-speed video camera
Maximum photographing speed 2 000 frames/s

In the experiment, the mold was set between the X-ray source and image intensifier and the mold filling sequence was observed. We also measured pressure changes in the mold cavity with a small semiconductor pressure sensor. **Figure 8** shows the comparison between simulation and experiment results. **Figure 8-(a)** shows the results of direct observation. Gas entrapment was observed in the corner portion where the poured melt becomes the horizontal portion from the vertical portion. The final filling position is the top. The back pressure in the cavity became almost constant after 0.07 s and the maximum pressure was about 2.5 kPa.

4.2 Simulation

The calculation was made with void fraction of mold 0.375, permeability of sand [15] $K_m = 1.56 \times 10^{-9}$ m^2, permeability of coating $K_c = 1.5 \times 10^{-13}$m^2, and thickness of coating 0.1 mm. **Figure 8-(b)** shows simulation results of mold filling sequence and also the gas pressure contour in the sand mold. **Figure 8** shows that the gas entrapment observed through the experiment and final filling position

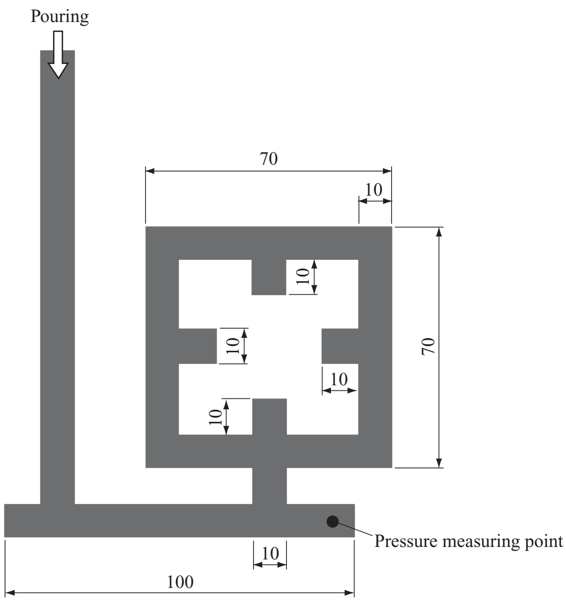

Fig. 7 Fran mold for gravity casting (unit : mm)

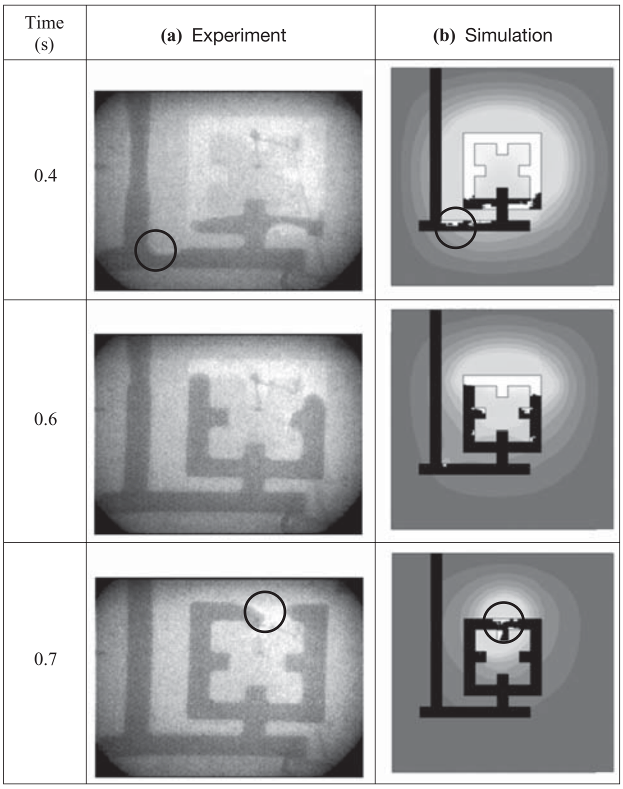

Fig. 8 Comparison of observed and simulated results

agree well. In the corner portion of the runner, the gas pressure in the sand mold is high, and so the gas in the cavity remains without being discharged. **Figure 9** shows pressure changes in the mold. The measured pressure change in the cavity and the calculation results agree well, validating this calculation method. **Figure 9** shows the results when the permeability of sand was 1/10 ($K_m = 1.56 \times 10^{-10} \mathrm{m}^2$) and permeability of coating 1/5 ($K_c = 7.5 \times 10^{-14} \mathrm{m}^2$), and from these results, it can be said that the permeability gives a big effect to the pressure in the cavity. Especially the pressure in the cavity greatly changes due to the coating, indicating that using a proper coating is important for controlling the (gas defect) entrapment defect.

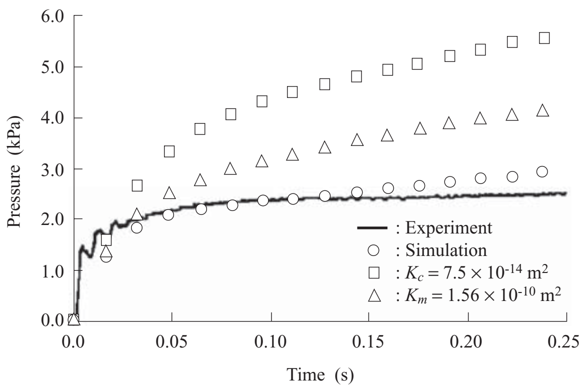

Fig. 9 Pressure change in mold cavity

5. Application to actual products

Figure 10 shows an example of the simulation applied to a 4-cylinder engine block manufactured by sand mold casting. In this casting design, overflow and open riser are set to discharge air in the mold. But a large gas entrapment defect occurred at the portion A of **Fig. 10-(a)**. The reason is considered to be that the gas in the mold was not sufficiently discharged through the overflow, open riser, and mold. **Figure 10-(c)** shows the gas defect prediction results by simulation, and they agree well with the gas defects occurring with the product, indicating that this method can be applied to actual products.

6. Conclusion

In this study, a simulation code capable of considering the gas escape through the sand mold and vent was developed in consideration of the back pressure by Direct Finite Difference method, and the following conclusions were obtained.

(1) A method was proposed to predict gas defects entrapped in the mold filling sequence. This method can predict both very small gas defects and large gas defects.

(2) In the metalic mold casting, the back pressure has effects on mold filling pattern and final position.

(3)A comparison of the results of X-ray direct observation experiments and verification/experiment results obtained through gas pressure measurement showed the filling pattern was in good agreement and the pressure measurement results were also in agreement, confirming the validity of this code.

(4) Since this method can predict gas entrapment defects in sand mold casting, it will be a useful tool for optimizing defect-free casting designs.

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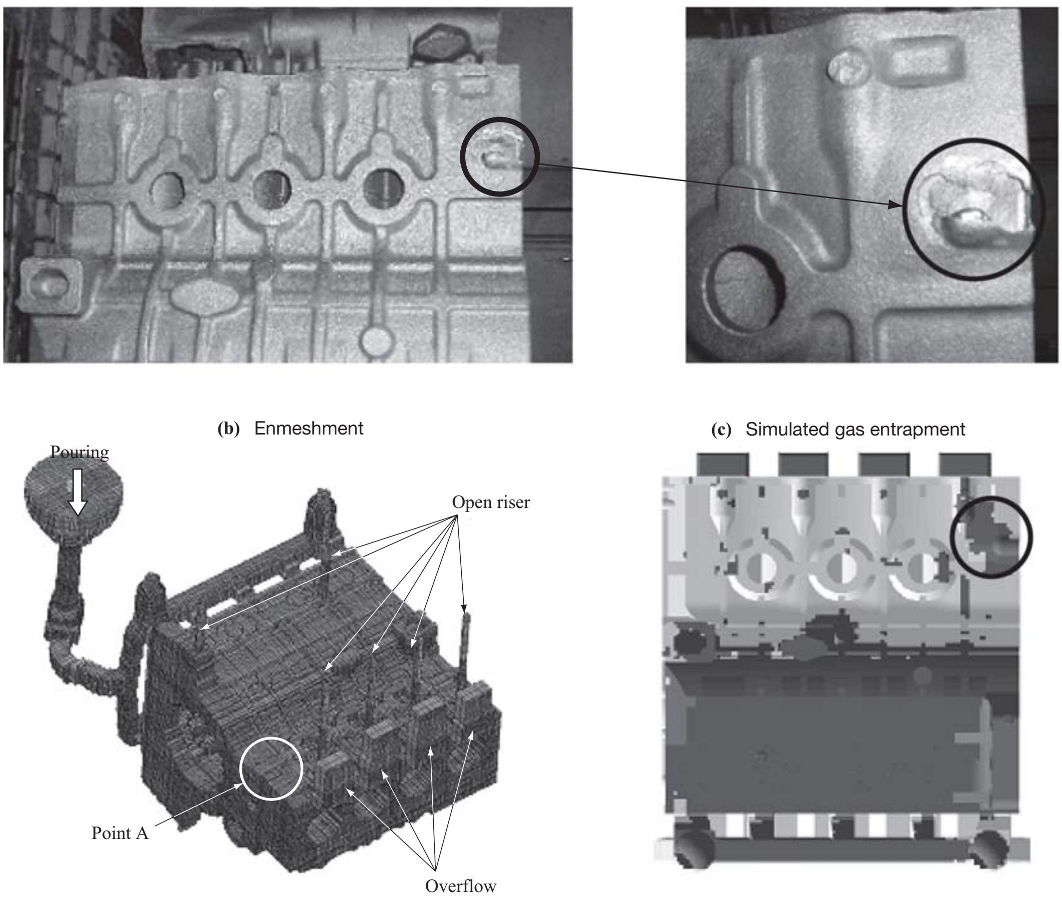

(a) Observed gas defect in product
(b) Enmeshment
(c) Simulated gas entrapment

Fig. 10 Gas defect in 4-cylinder engine block

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