

# Development of High-Pressure Die-Casting Simulation and Verification in Motorcycle Parts

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## ABSTRACT

The quantitative evaluation of trapped air and strength of cast products at the completion of solidification in high pressure die-cast has been studied using material test and simulation. As a result, the prediction accuracy of trapped air analysis was enhanced by considering back pressure. In addition, by coupling the trapped air defect at the completion of flow with the solidification process, the analysis of mechanical characteristics of cast products has become possible.

## 1. Introduction

Motorcycle frame parts are being increasingly made of aluminum for the purposes of weight reduction. These frame parts are joined with aluminum extruded tubes, and have conventionally been manufactured by the gravity die-casting method in consideration of weldability. The high-pressure die-casting method is suitable for further weight reduction of frame parts from the perspectives of thickness, high accuracy and high productivity. However, conventional high-pressure die-casting methods have been considered unsuitable for welding.

In order to resolve these issues, efforts are being made to create die-cast frame parts using transition flow filling method die-casting<sup>(1)</sup>. In addition, hollow structural castings that can be welded and offer high strength and rigidity have recently been manufactured by transition flow filling method die-casting and commercialized in response to increasing demands for weight reduction<sup>(2)</sup>. As an

additional method, there are also cases where the high-pressure die-casting method has been successfully applied to frame parts by increasing the vacuum inside the die cavity to reduce the amount of air trapped inside high-pressure die-cast products<sup>(3)</sup>.

Developing these cast products in a short time requires technology for predicting formability, weldability, strength, quality and other properties in the early development stages. However, it is not easy for conventional casting simulations to quantitatively analyze the amount of trapped air. On the other hand, high-pressure die-cast products do not have uniform internal quality so the strength differs depending on the product position, and developing methods for predicting the actual strength is desired to achieve further weight reduction.

This paper discusses an outline of a newly developed method for analyzing trapped air and actual strength in the high-pressure die-casting method, and reports the correlation between actual cast products and simulation results.

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## 2. Comparison with Conventional Technology

Recent casting simulations have often been performed with the aim of enhancing casting quality. Conventional casting simulations individually analyze the behavior of molten metal in the flow processes, changes in physical properties, or the generation of shrinkage cavities in the solidification processes, and these separate simulations have been used as necessary. It has been possible to predict defects and to qualitatively analyze casting designs for general casting, even by using these methods. However, most conventional casting simulations do not take into account the effects of back pressure inside the die cavity, so analysis was performed using constant pressure inside the die cavity. This made it unlikely to predict the amount of trapped air with sufficient accuracy, which limited these methods to qualitative evaluation. Therefore, this study took into account back pressure in addition to the conventional analysis methods and dealt with the two-phase flow of the gas and liquid phases. This made it possible to analyze the pressure gradient of the air inside the die cavity, and enhance the quantitative prediction accuracy of the amount of trapped air.

In addition, instead of analyzing the injection of molten metal from the biscuit, based on the boundary condition settings, the behavior of the molten metal inside the sleeve was also analyzed in order to perform more accurate flow simulations.

On the other hand, air that becomes trapped during the molten metal flow ultimately becomes porous within the cast product as shrinkage cavities occur during solidification. However, conventional solidification analysis is unable to account for the trapped air at the completion of filling in the initial solidification stages. This made it unlikely to accurately analyze the size and amount of porosity. These items must be taken into account, particularly for die-cast products where air becomes trapped in the filling process. The newly developed method made it possible to quantitatively analyze the size and amount of porosity at the completion of solidification by coupling the trapped air at the completion of the flow state with that of the solidification process. In addition, the strength and elongation could also be predicted by taking into account dendrite arm spacing (DAS) and segregation.

solidification time method, temperature gradient method, corrected temperature gradient method ( $G/\sqrt{R}$  method), and so on<sup>(6)</sup>. However, these methods do not sufficiently take into account the porosity creation mechanism, so it was difficult to quantitatively predict the position and size to which porosity would be created. Therefore, simulations were conducted by modeling the principle of solidification porosity creation as shown by the images in Fig. 2. Initially, small porosities form at the root of dendrites, then the small porosities grow in size and separate from the root of the dendrites as solidification progresses. Then, as solidification progresses further and the dendrites contact each other, the porosities which have moved between the dendrites grow to compensate for solidifying contraction and become shrinkage cavities. The basic equations for these simulations are shown by (1) to (4) below<sup>(7)</sup>. In addition, Fig. 3 shows the flow chart for predicting defects.

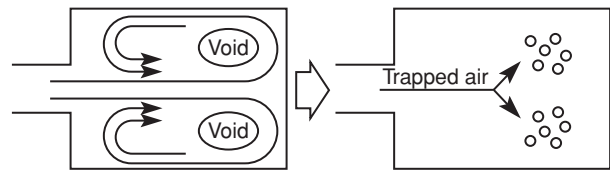


Fig. 1 Mechanism of trapped air evolution

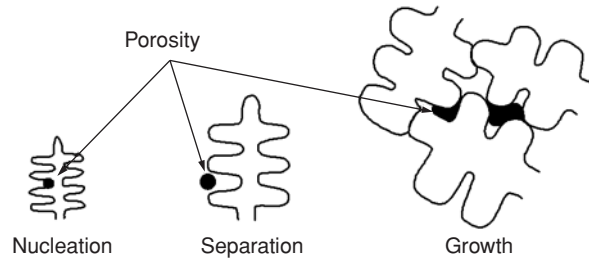


Fig. 2 Principle of porosity creation

## 3. Casting Simulations

### 3.1. Flow Simulations

Flow simulations allowed analysis by modeling the trapped air as shown by the image in Fig. 1. First, the occurrence of voids was predicted by solving the free surface by the Volume of Fluid (VOF) method<sup>(4)</sup>. In this case a void is a macro cavity expressed as an aggregation of multiple mesh elements. When a void occurs during the course of the flow simulation, the equation of conservation is solved. The void is then reduced to the size of a single element or less and disappears when the molten metal is filled. Trapped air the size of a single element or less is judged to have been generated at the point this macro cavity disappears. The size, gas pressure and number of trapped air locations are calculated. After that the size and gas pressure of the trapped air changes as the trapped air moves along with the molten metal flow<sup>(5)</sup>.

### 3.2. Solidification Simulations

On the other hand, methods for predicting defects in conventional solidification simulations include the isothermal method,

- (1) Equation of heat transfer

$$C\rho \frac{\partial T}{\partial t} = \lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) - \rho L \frac{\partial f_L}{\partial t} \quad (1)$$

$C$ : Specific heat,  $\rho$ : Density,  $T$ : Temperature,  
 $t$ : Time,  $\lambda$ : Thermal conductivity,  $L$ : Latent heat,  
 $f_L$ : Liquid phase ratio

- (2) Equation of continuity

$$\left( \frac{\rho_s}{\rho_L} - 1 \right) \frac{\partial f_L}{\partial t} - \frac{\partial f_L u}{\partial x} - \frac{\partial f_L v}{\partial y} - \frac{\partial f_L w}{\partial z} + \frac{\partial f_v}{\partial t} = 0 \quad (2)$$

$\rho_s, \rho_L$ : Solid phase and liquid phase density  
 $u, v, w$ : Flow speed between dendrites  
 $f_v$ : Volume ratio of porosity

- (3) Equation of motion

$$u = -\frac{k}{\mu f_L} \frac{\partial P}{\partial x} \quad v = -\frac{k}{\mu f_L} \frac{\partial P}{\partial y} \quad w = -\frac{k}{\mu f_L} \frac{\partial P}{\partial z} \quad (3)$$

$$k : \text{Permeability} = \frac{f_L^3 d^2}{180(1 - f_L)^2} \quad \mu : \text{Coefficient of viscosity}$$

$d$  : Dendrite cell size

## (4) Gas volume conservation

$$[H_0] = (1 - f_L)[H_S] + f_L[H_L] + \alpha_H \frac{P_g f_v}{T} \quad (4)$$

$[H_0]$  : Total gas volume,  $[H_S]$  : Gas volume in solid phase,

$[H_L]$  : Gas volume in liquid phase,  $\alpha_H$  : Coefficient,

$P_g$  : Gas pressure within the porosity

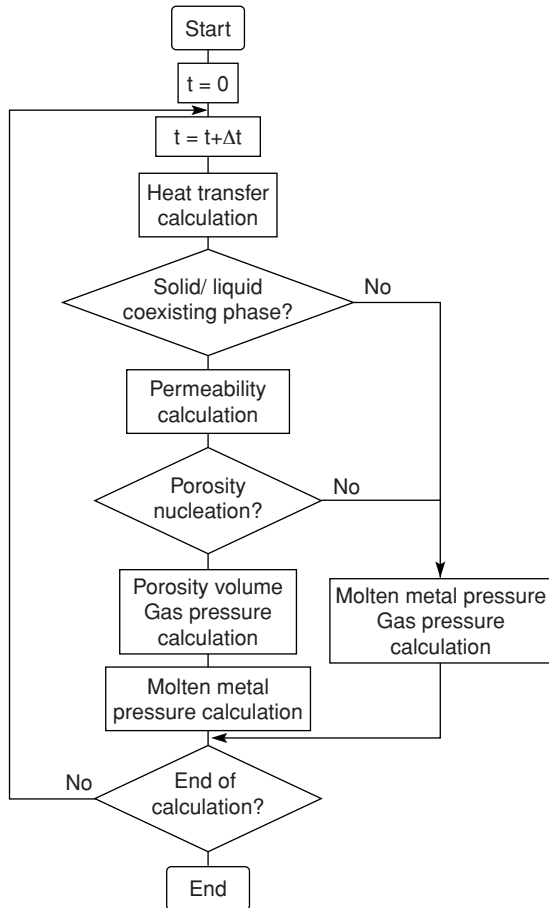


Fig. 3 Flow chart for predicting of defects

#### 4. Comparison of Simulations and Actual Measurements

##### 4.1. Transition Flow Filling Method Die-Cast

First, comparisons were performed for transition flow filling method die-casting which has a slower inlet velocity of molten metal than general high-pressure die-casting which also requires a weldability judgment. The flow and solidification simulation results were compared using the pivot plate shown in Fig. 4 which is a motorcycle frame part. The plunger velocity was 1.8 m/s, and overflows were set in five locations, of which three had reduced pressures. Test pieces were taken from general surfaces and used in experiments to measure various properties. In addition, the simulations used 137 285 mesh elements, and the physical property of the molten metal used the values for Al-5%Mg-0.7%Mn-0.8%Ni materials.

##### 4.1.1. Air trap simulation

Figure 5 shows the simulation results for the amount of trapped air. (a) and (b) show different casting designs, the amount of trapped air measured was 3.6 and 2.0 cm<sup>3</sup>/100 g Al, respectively. With conventional analysis that does not take into account back pressure, these values were 1.7 and 2.4 cm<sup>3</sup>/100 g Al, respectively, also the accuracy deteriorated for both the trapped air trend and absolute values. In contrast, the new analysis method that takes into account back pressure produced the values of 3.1 and 1.9 cm<sup>3</sup>/100 g Al, respectively, indicating enhanced accuracy for both the trend and absolute values. This is thought to be because taking the back pressure into account brought the simulated molten metal filling pattern closer to the actual pattern. In addition, the casting was also found to be of a weldable level even at the last part the molten metal fills.

##### 4.1.2. Amount and size of porosity

Figure 6 (a) and (b) show the simulation results for the amount and size of porosity, and Figs. 7 and 8 compare the simulated values and measured values. The horizontal axes show the simulated values and the vertical axes show the measured values. The measured values are slightly higher for both the amount of porosity and the porosity size, but the overall trends match well. The amount of porosity in the product was 0 to 0.02%, and the porosity size was 10 to 80 μm depending on the position. The amount and size of porosity both tended to increase in positions with large amounts of trapped air or a slow solidification rate.



Fig. 4 Pivot Plate

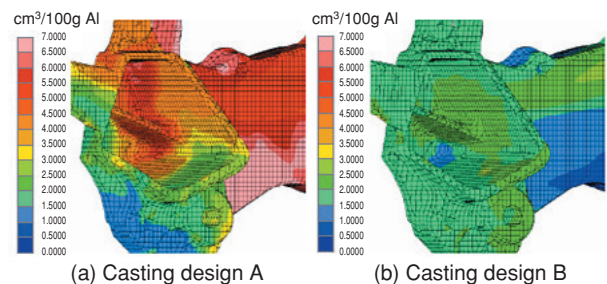


Fig. 5 Example of trapped air simulation with consideration to back pressure

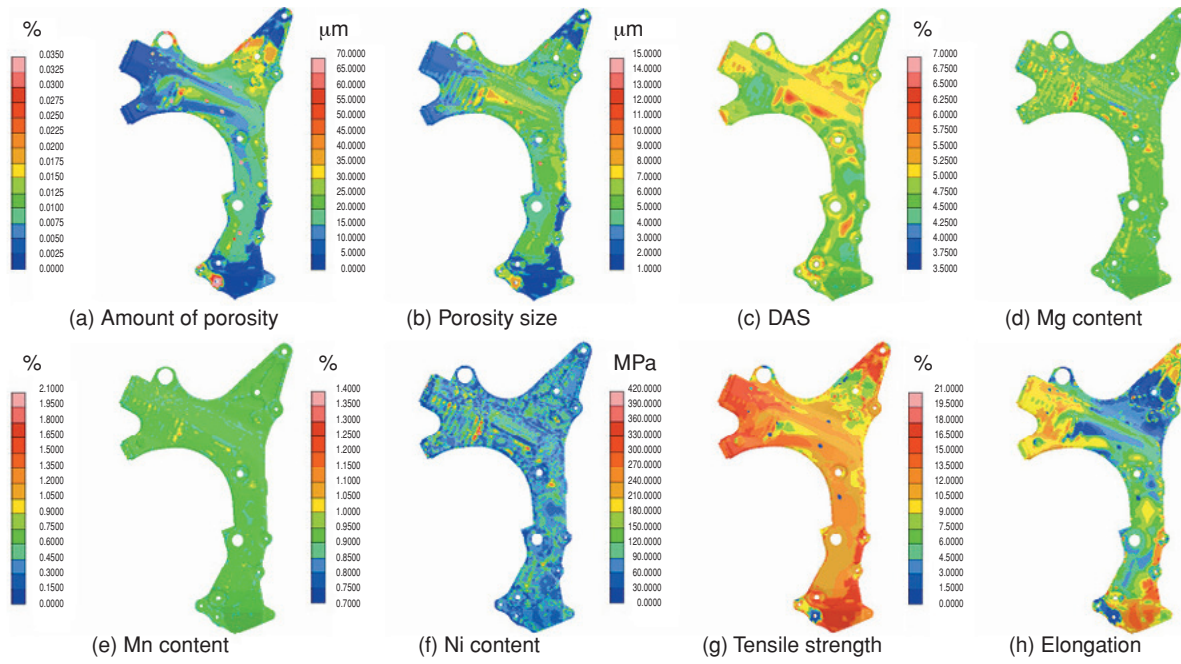


Fig. 6 Simulation results of pivot plate

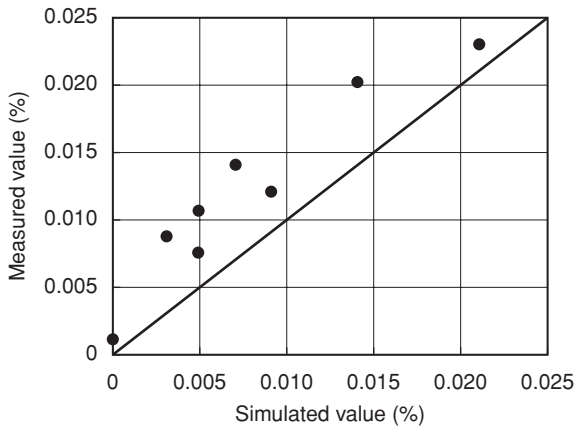


Fig. 7 Comparison of amount of porosity

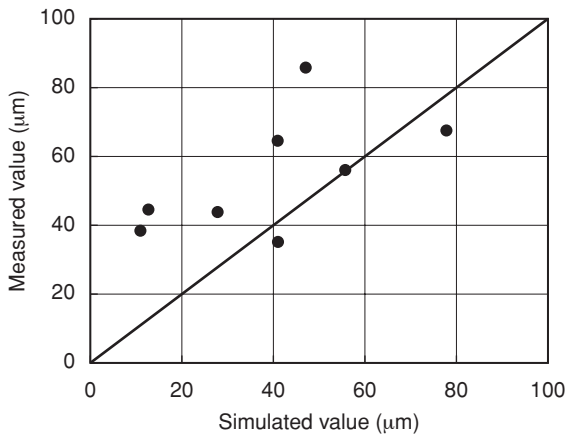


Fig. 8 Comparison of porosity size

#### 4.1.3. Dendrite arm spacing (DAS)

Figure 6 (c) shows the DAS simulation results, and Fig. 9 compares the simulated values and measured values. This shows that the measured values and the simulated values match closely, with the DAS between 6.5 and 9  $\mu\text{m}$  depending on the position. There was little difference in the DAS between positions, and the DAS was approximately the same as that of general high-pressure die-casting. This indicates that transition flow filling method die-casting provides the same cooling rate as that of general high-pressure die-casting.

#### 4.1.4. Chemical composition

Figure 6 (d), (e) and (f) show the simulated values for each chemical composition, and Fig. 10 compares the simulated and measured chemical composition values. This shows that the measured values and simulated values match relatively well for each element. These distributions of Mg, Ni and Mn concentrations indicate that macro segregation exists throughout the entire casting. This type of macro segregation produces uneven mechanical, chemical and physical properties in die-cast products, and also often occurs in the same positions as micro-porosity<sup>(8)</sup>.

#### 4.1.5. Tensile strength and elongation

Figure 6 (g) and (h) show the simulation results for tensile strength and elongation, and Figs. 11 and 12 compare the simulated values and measured values. This shows that both tensile strength and elongation match relatively well. The tensile strength and elongation were 195 to 285 MPa and 2 to 10.6% respectively. Both tensile strength and elongation tended to decrease locally in positions with high porosity. This is because an Al-Mg alloy was used. That is to say, in contrast to Al-Si alloys which have a skin-formed type solidification format, Al-Mg alloys have a mushy type solidification format. For this reason, primary crystal  $\alpha$ -Al dendrites crystallize throughout the entire casting in the initial solidification stages. The gaps between these dendrites act as pressure transmission routes, resulting in an early loss of molten metal pressure. As a result, pressure is not sufficiently transmitted in positions removed from the gates, so the porosity size is larger and the tensile strength and elongation values are lower than in other

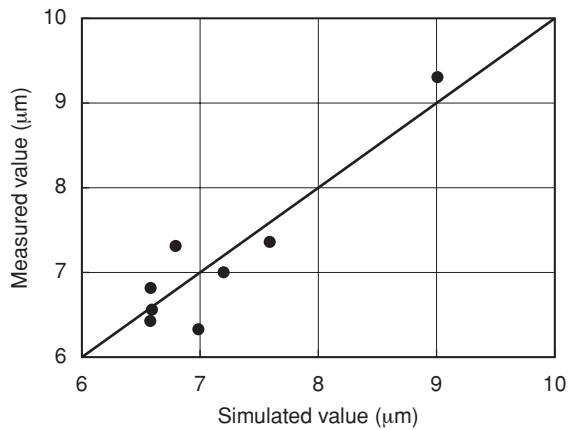


Fig. 9 Comparison of DAS

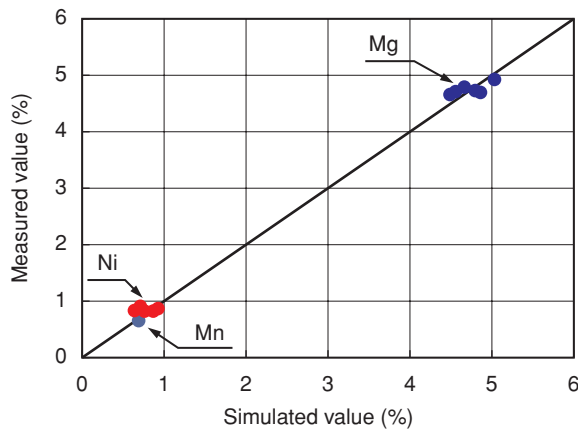


Fig. 10 Comparison of chemical composition

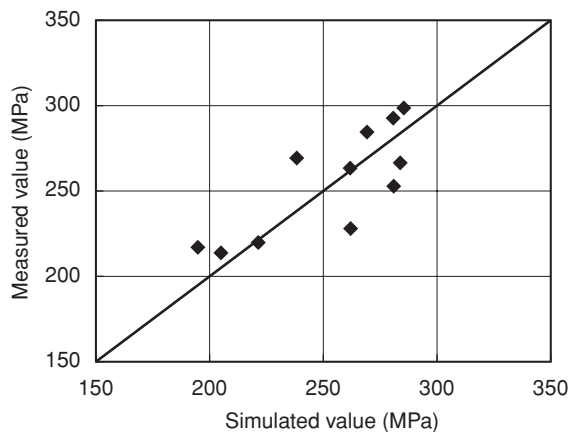


Fig. 11 Comparison of tensile strength

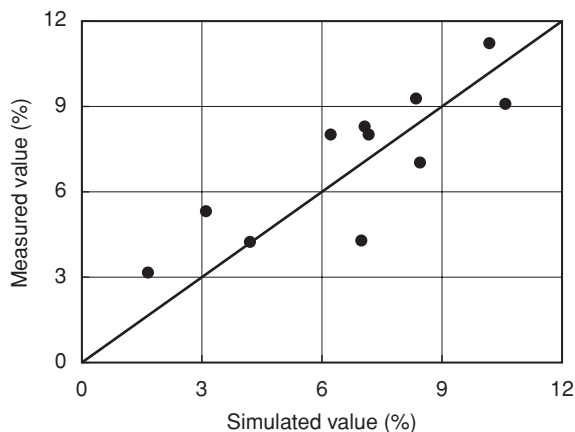


Fig. 12 Comparison of elongation

positions. These tendencies are more pronounced for Al-Mg alloys than for Al-Si alloys.

#### 4.2. High-pressure Die-cast

Verification with transition flow filling method die-casting confirmed a correlation between the simulated and measured values, so next verification was conducted with high-pressure die-casting. The flow simulation results for high-pressure die-casting were compared using the clutch outer shown in Fig. 13. The plunger velocity was 2 m/s, and overflows were set in seven locations, of which five were connected to vents. Test pieces were taken from the fin parts and used in experiments to measure various properties. The simulations used 51 723 mesh elements, and the physical property of the molten metal used the values for JIS ADC12 equivalent materials.

##### 4.2.1. Air trap simulation

Figure 14 (a) shows the simulation results for the amount of trapped air, and Fig. 15 compares the simulated and measured values. The horizontal axes show the simulated values and the vertical axes show the measured values. Analysis that does not take into account back pressure showed that when the air pressure inside the cavities increased, the air trapped in those positions was less than that of the actual volume. In addition, the filling pattern and the final filling position differed, so the trapped air volume also differed. However, the new analysis method that takes into account back pressure produced values that matched well in each position. The amount of trapped air inside the product was approximately 2 to 10 cm<sup>3</sup>/100 g Al. The difference in trapped air volume between positions is mainly due to the flow length, with more air becoming trapped as the flow length increases.

##### 4.2.2. Amount and size of porosity

Figure 14 (b) and (c) show the simulation results for the amount and size of porosity, and Figs. 16 and 17 compare the simulated and measured values. The newly developed simulation method coupled the amount and size of trapped air, etc. at the completion of the flow state with the solidification analysis, so both the amount and size of porosity matched relatively well with those of the measured values. The amount of porosity in the product was 0 to 0.047%, and the porosity size was 20 to 330 μm depending on the position. The amount and size of porosity both tended to increase in positions with large amounts of trapped air or a slow solidification rate.

##### 4.2.3. Dendrite arm spacing (DAS)

Figure 14 (d) shows the DAS simulation results, and Fig. 18 compares the simulated and measured values. In contrast to the results for transition flow filling method die-casting using an Al-Mg alloy, the measured values were larger in these results. This is due to the difference in the alloys rather than the casting methods. Al-Mg and other metal-metal element alloys are generally in

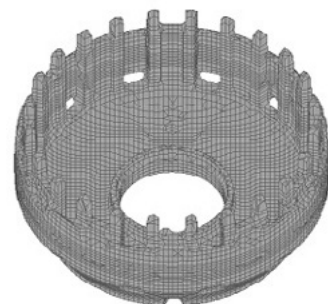


Fig. 13 Clutch outer

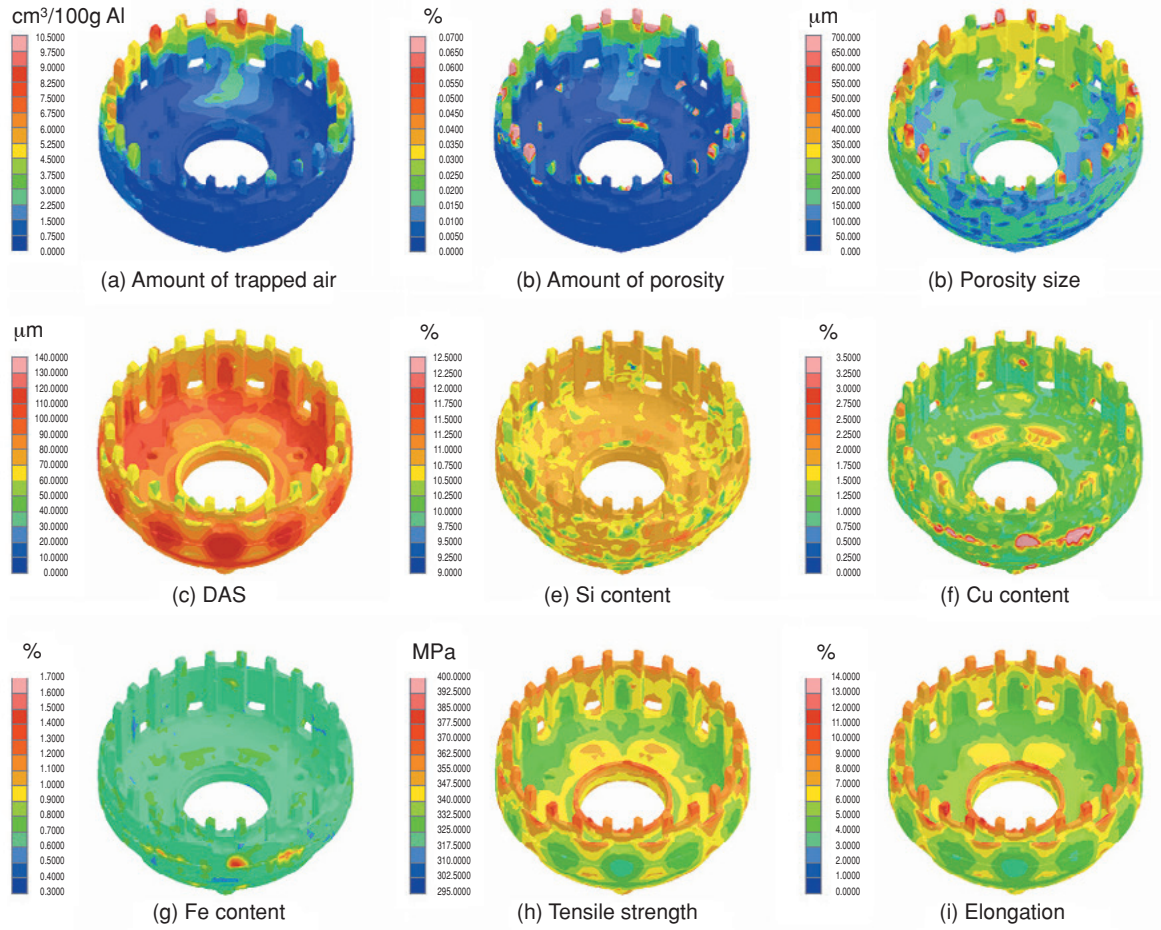


Fig. 14 Simulation results of clutch outer

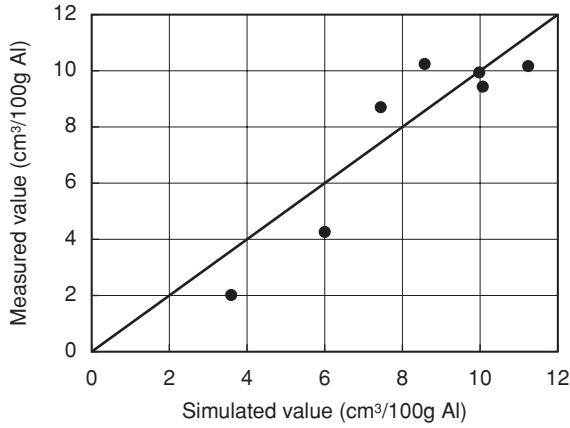


Fig. 15 Comparison of trapped air

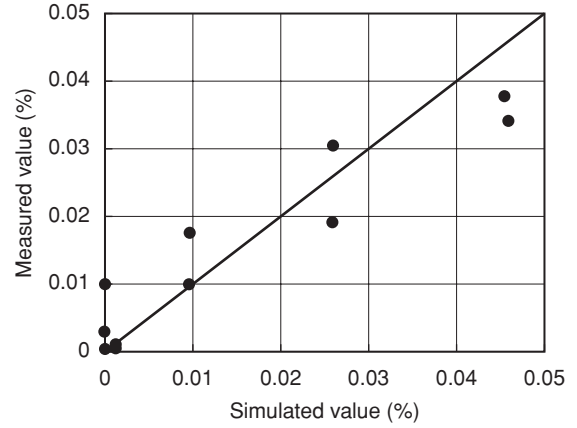


Fig. 16 Comparison of amount of porosity

equilibrium at the interface of solid phase and liquid phase, which presents no issue. However, Al-Si and other metal-metalloid element alloys undergo facet-nonfacet eutectic solidification, so a relatively large supercooling occurs at the interface of solid phase and liquid phase. This supercooling significantly affects the solidification pattern and the micro structure. The analysis program used in this study performed equilibrium solidification analysis, but it is thought that the prediction accuracy can be enhanced by performing nonequilibrium solidification analysis.

#### 4.2.4. Chemical composition

Figure 14 (e), (f) and (g) show the simulated values for each chemical composition, and Fig. 19 compares the simulated and measured chemical composition values. The measured and simulated values match well, and these distributions of Si, Cu and Fe concentrations indicate that macro segregation exists throughout the entire casting. The ease by which macro segregation occurs is thought to be more due to permeability than the solidification rate.

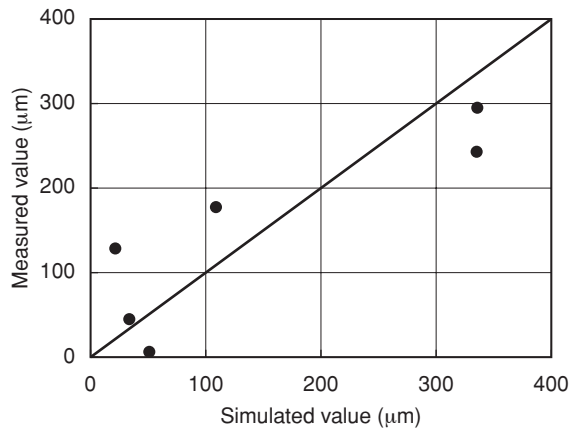


Fig. 17 Comparison of porosity size

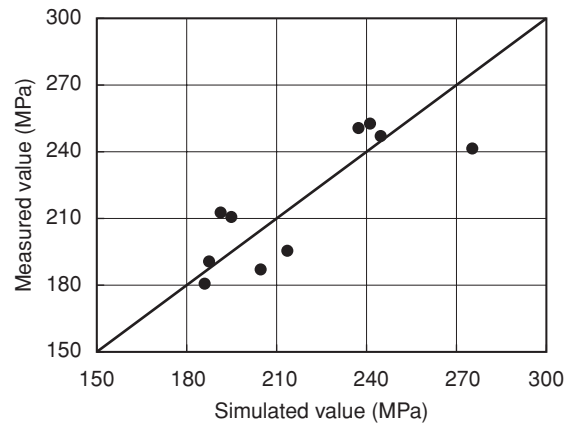


Fig. 20 Comparison of tensile strength

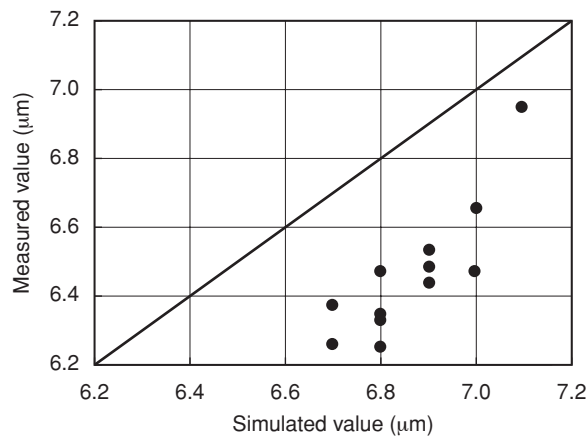


Fig. 18 Comparison of DAS

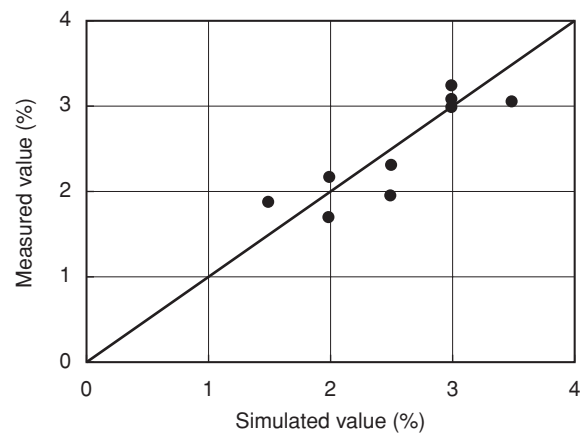


Fig. 21 Comparison of elongation

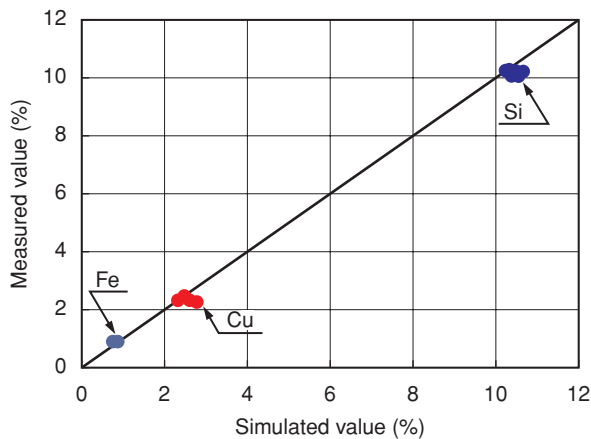


Fig. 19 Comparison of chemical composition

#### 4.2.5. Tensile strength and elongation

Figure 14 (h) and (i) show the simulation results for tensile strength and elongation, and Figs. 20 and 21 compare the simulated and measured values. Both the tensile strength and elongation values match relatively well despite a low DAS correlation as described in 4.2.3. This is thought to be because there is almost no change in the mechanical properties due to the DAS in rapidly cooled structures 10  $\mu\text{m}$  or smaller such as high-pressure die-casting.

## 5. Conclusion

A system for coupling the air trapped during the molten metal flow with the solidification process in casting simulations was developed, and the following results were obtained.

- (1) Analysis that coupled the process from flow analysis to solidification analysis was possible.
- (2) Taking into account back pressure in flow analysis enhanced the quantitative prediction accuracy of the amount of trapped air inside products.
- (3) Quantitative analysis of the amount and size of porosity in solidification analysis was possible.
- (4) Taking into account the amount and size of porosity in the DAS and segregation analysis results also made it possible to analyze the tensile strength and elongation.

Various casting simulation methods are currently being investigated, and the system developed in this study is thought to indicate a new direction for casting simulations. Further enhancements in accuracy and expanded applications are anticipated in the future.

## 6. Acknowledgements

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