Numerical Analysis Verification of Quality Improvement Effect of Small Volume Solid Phase Die Casting Method by Controlling Molten Metal Temperature

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Abstract: Semi-solid die casting, which employs a partially molten slurry, has been widely recognized as an effective method to improve the quality of die-cast products. However, the addition of a slurry preparation process increases manufacturing costs, presenting a significant drawback. To address this issue and achieve a substantial reduction in energy consumption during the manufacturing process, a novel method named Partial Solid Die Casting (PSDC) has been proposed. In PSDC, the molten metal temperature is lowered to near the liquidus temperature of the alloy, thereby enabling control of the solid fraction in the sleeve immediately before injection to a maximum of approximately 0.05. This promotes nucleation during solidification and contributes to enhanced casting quality in thick sections. Moreover, the cycle time is reduced by 24% to raise the die temperature, which ultimately leads to a 38% reduction in energy consumption during production. In this study, a comprehensive simulation model was developed to accurately evaluate the solid fraction within the sleeve, incorporating the ladle pouring process, injection mechanism motion, and pressure intensification timing. The developed analysis method numerically demonstrated the formation of a solid–liquid coexisting molten metal in the sleeve and clarified the beneficial effects of pressure intensification timing on product quality.
Keywords: Semi-solid, die-casting, Solidification nuclei, full model simulation

1 Introduction

Improving the quality of die-cast products has been a continuous pursuit, and semi-solid die casting, which utilizes a partially molten slurry, has gained attention as a promising approach [1]. However, this method poses challenges such as increased production costs due to the additional slurry preparation process and limited applicability to eutectic alloys with narrow solidification ranges, such as ADC12. To overcome these challenges, Itamura et al. proposed a semi-solid casting method using a hypoeutectic aluminum alloy (AC4CH), in which the molten metal temperature inside the injection sleeve is carefully controlled [2]. More recently, Koide et al. reported the successful practical implementation of a semi-solid process using ADC12 alloy in existing die casting lines, demonstrating the increasing feasibility of semi-solid technology in commercial production [3]. Koide's method replaces forged components with cast parts using semi-solid technology, achieving both high quality and mass productivity. On the other hand, Itamura focused on replacing zinc die casting with aluminum by improving surface roughness and dimensional accuracy, thereby contributing to product weight reduction. Their approach emphasized increasing the number of α-Al nuclei formed within the sleeve to promote fine spherical crystal formation through temperature control, leading to improved casting quality.

Based on these developments, this study proposes a new method—Partial Solid Die Casting (PSDC). The PSDC process aims to promote dispersion of porosity and local solidification in thick sections by generating a small number of α-Al nuclei in the molten metal inside the sleeve and increasing the number of nucleation sites by the time filling is completed. Various methods for reducing porosity in thick sections have been previously proposed, such as secondary pressure application [4] and high-speed injection under high J-Factor [5]. PSDC incorporates the latter approach to enhance the pressure intensification effect.

To verify the quality improvement effect of PSDC, the present study constructed a simulation model focusing on three key aspects:

1.Modeling the ladle, injection mechanism, and die to accurately calculate the solid fraction in the sleeve.

2.Pressure analysis considering the timing of pressure intensification.

3.Porosity prediction using a dedicated algorithm that accounts for solidification nucleation.

Using this comprehensive model, the entire casting process was simulated, and the effectiveness of PSDC was quantitatively verified. This paper presents the outline of the PSDC process and discusses the effects of casting conditions on solid fraction distribution and casting pressure based on the simulation results.

2. Overview of PSDC Method

In the PSDC process, the primary parameter for controlling the solid fraction of the molten metal in the injection sleeve is the molten metal temperature. When the molten metal temperature is reduced to near the liquidus point, there is a risk that Cold Flakes formed on the inner wall of the sleeve may flow into the product. Previous studies have suggested that the flow of such Cold Flakes into the cavity becomes significant when the solid fraction exceeds 0.1 [6]. Therefore, in this study, the target upper limit for the solid fraction was set to approximately 0.05 to avoid this issue.

Lowering the molten metal temperature also reduces the thermal load on components of the injection system. This suppresses phenomena such as galling between the sleeve and the plunger tip and the formation of burrs around the tip. Furthermore, stable injection operation can be maintained even under high J-Factor conditions, where higher injection speeds are used, resulting in enhanced pressure intensification effects.

Additionally, by reducing the biscuit thickness and decreasing the molten metal supply volume, the solidification of the biscuit region is completed earlier, thereby shortening the cycle time. Although these measures reduce the heat input to the die, the shorter cycle time allows the die to maintain a relatively high temperature, while also decreasing the temperature fluctuation within a single casting cycle.

Through these combined effects, the PSDC process not only improves the casting quality in thick sections and ensures stable casting conditions but also contributes significantly to reducing the thermal energy required during the casting process.

3.Experimental Results

3.1 Experimental Conditions

To evaluate the effectiveness of the PSDC process, a comparative experiment was conducted between a conventional condition with a relatively high molten metal temperature (hereinafter referred to as general DC) and the proposed PSDC process.

The casting experiment was carried out using a 350-ton die casting machine. A die designed for a product with a mass of 850 g and a minimum wall thickness of 5 mm was used. The geometry of the product is shown in Figure 1. JIS ADC12 alloy was used as the material, and the die cavity was operated under a reduced pressure of −80 kPa relative to atmospheric pressure. Regarding the wall thickness of 5 mm was used. The geometry of the product is shown in Figure 1. JIS ADC12 alloy was used as the material, and the die cavity was operated under a reduced pressure of −80 kPa relative to atmospheric pressure. Regarding the shown in Table 1.

As a result of reducing the molten metal temperature, biscuit thickness, and cycle time in the PSDC condition, the total thermal energy consumed during the casting stage was reduced by approximately 38% compared to the general DC process.

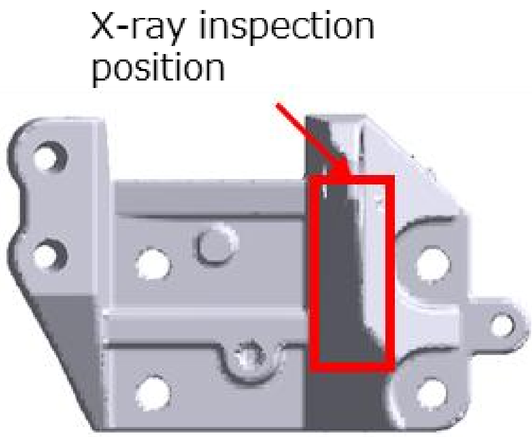

Fig. 1: Geometry of the cast product.

Table 1: Comparison of casting conditions between PSDC and general DC.

Item	PSDC	General DC
Molten Metal Tempe. (℃)	605	640
Low injection speed (m/s)	0.27	0.15
High injection speed (m/s)	3.2	2.7
Casting pressure (MPa)	65	50
Stamp Thickness (mm)	20	45
Injection delay time(s)	0	1.0
Cycle time (s)	41.0	53.9
J-Factor	1412	1056
Pressure intensification time (ms)	45	50

3.2 Experimental Results

Under the PSDC condition, die casting was performed at a molten metal temperature 17 ° C above the liquidus temperature of ADC12. No surface defects such as cold shuts or weld lines were observed in the final product. Furthermore, by increasing the J-Factor, which is defined by the gate geometry and gate velocity, the pressure intensification time was reduced by approximately 10% compared to the general DC condition. Figure 2 shows X-ray transmission images of the region indicated in Figure 1. While porosity was observed under the general DC condition, no porosity was detected under the PSDC condition.

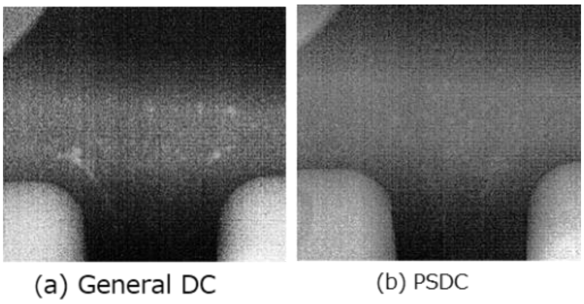

Fig. 2: Comparison of X-ray transmission images of thick sections.

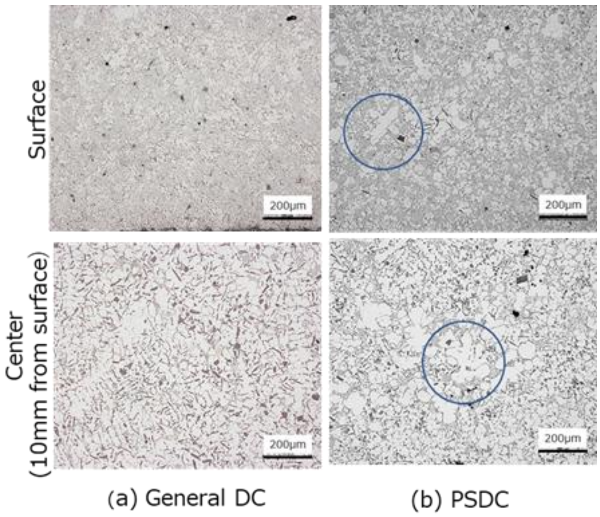

Fig. 3: Comparison of microstructures in the cast product.

Figure 3 compares the internal microstructure of the castings, focusing on a central area 10 mm below the surface. In the PSDC sample, dendritic structures of early-stage Al-α crystals, indicated by circles in the figure, were observed. These Al-α crystals are considered to have formed in regions with relatively higher solid fraction within the sleeve and were dispersed throughout the product during injection.

In contrast, nuclei formed in regions with lower solid fractions likely acted as initial sites for solidification in the thick sections of the product, contributing to both the dispersion and reduction of porosity.

4. Numerical Validation of Solid Fraction Control in PSDC

4.1 Computational Models

To verify the experimental results, two computational models were constructed and analyzed using the finite element method software CAPCAST. The structure of each model is shown in Figure 4.

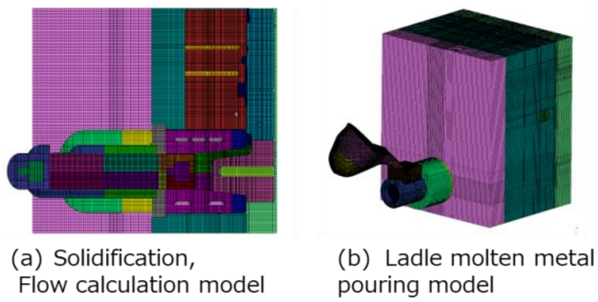

Fig. 4: Computational models used in the analysis.

Model (a) was used to calculate the temperature distribution of the entire die, including the plunger tip and sleeve sections. The minimum mesh size was 1.5 mm, and the total number of elements was approximately 5.3 million.

Model (b) was developed to evaluate the solid fraction distribution of the molten metal inside the sleeve at the end of ladle pouring. This model includes the die, injection system, and ladle components. The mesh size in key areas was the same as in model (a), and the total number of elements was approximately 6.23 million.

The temperature distribution of the molten metal inside the sleeve obtained from model (b) was mapped as the initial molten metal condition in model (a), enabling integrated flow and solidification analysis.

In the PSDC process, shortening of the cycle time is achieved through effective cooling of the plunger tip and the biscuit region. Therefore, the cooling pipes of the plunger tip were also incorporated into the model.

4.2 Simulation Method for the Sleeve Injection Area

Thermal analysis of the die including the sleeve injection area was conducted for four molten metal-filling states:

1.Plunger position before ladle pouring

2.Plunger position immediately after ladle pouring

3.Plunger position at the transition from slow to fast shot

4.Plunger position at the end of cavity filling

Figure 5 shows the temperature distribution around the sleeve inlet under the PSDC condition. Measurement results confirmed that the temperature rises not only around the sleeve inlet but also in the upper part of the sleeve liner.

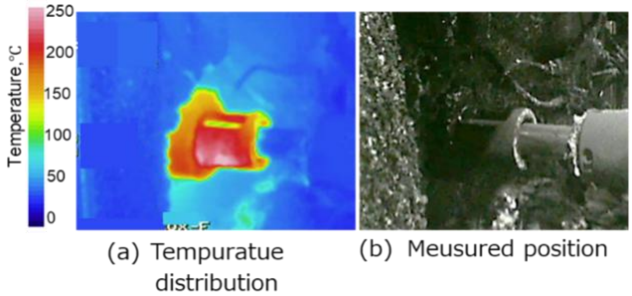

Fig. 5: Temperature distribution around the sleeve inlet under different conditions.

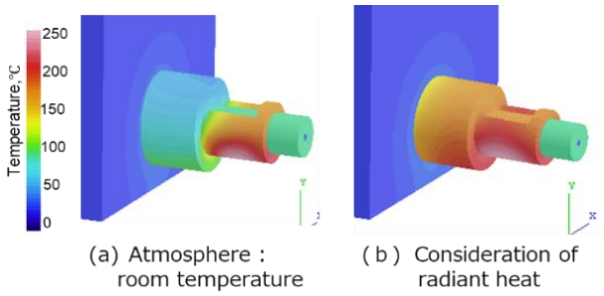

Fig. 6: Comparison of thermal boundary conditions and resulting temperature distributions.

Initially, a boundary condition assuming ambient air temperature was applied to the sleeve cavity immediately after die opening. The calculated temperature distribution under this condition is shown in Figure 6(a). Under this assumption, the lower part of the sleeve, which is in direct contact with the molten metal, became high in temperature, while the upper part near the sleeve inlet did not match the measured distribution due to a lack of molten metal contact.

During actual pouring, the area around the sleeve inlet is exposed to radiant heat from the molten metal, leading to localized temperature rise. Furthermore, although ambient air enters through the sleeve inlet after injection, the sleeve's internal temperature likely remains higher than room temperature between die clamping and the subsequent ladle pouring.

To reflect these real conditions, two additional thermal boundary conditions were introduced:

- During ladle pouring, radiant heat from the molten metal increases the internal air temperature of the sleeve
- Between die opening and pouring (and until fast shot initiation), residual heat from the die raises the internal air temperature of the sleeve

Figure 6(b) shows the recalculated temperature distribution incorporating these revised boundary conditions, which successfully reproduced the measured distribution shown in Figure 5.

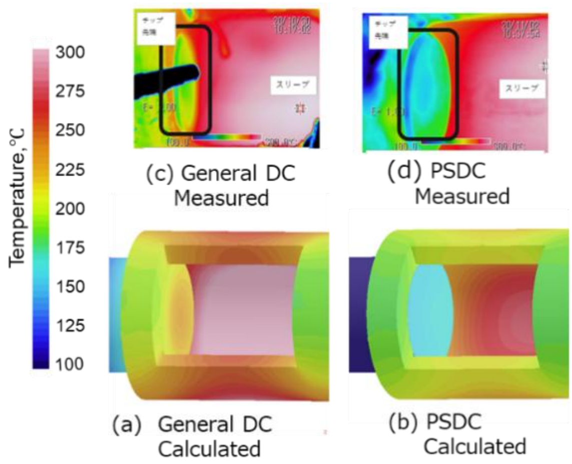

Fig. 7: Comparison of inner surface temperatures near the sleeve inlet.

5. Thermal Advantage of the PSDC Injection System

5.1 Temperature Reduction near the Sleeve Inlet

Figure 7 compares the measured temperatures at the sleeve inlet at the end of injection with those obtained by simulation. In the general DC condition, the shot time lag was set to 1 second, and the ladle pouring time was also relatively long. As a result, high-temperature molten metal remained in contact with the inner wall beneath the sleeve inlet for an extended period, leading to wall temperatures exceeding 300 ℃. In contrast, in the PSDC condition, the shot time lag was set to 0 seconds, and ladle pouring was completed in a shorter time. This suppressed the temperature rise of the inner sleeve wall, keeping it below 270 °C. This temperature reduction on the sleeve surface contributes to reducing galling between the sleeve and plunger tip, resulting in more thermally stable injection conditions in the PSDC process.

5.2 Reduction of Temperature Fluctuation across Sleeve Cross-Section

The temperature distribution along the cross-section of the sleeve in the injection direction was examined. Figure 8 presents a comparison of temperature distributions from just before ladle pouring to the completion of injection. Under the general DC condition, the temperature of the lower part of the sleeve remained above 300 °C until the end of filling, which is an unfavorable condition for smooth sliding of the plunger tip. In contrast, in the PSDC condition, the temperature decreased after the transition to the high-speed shot phase, suggesting improved stability in plunger movement.

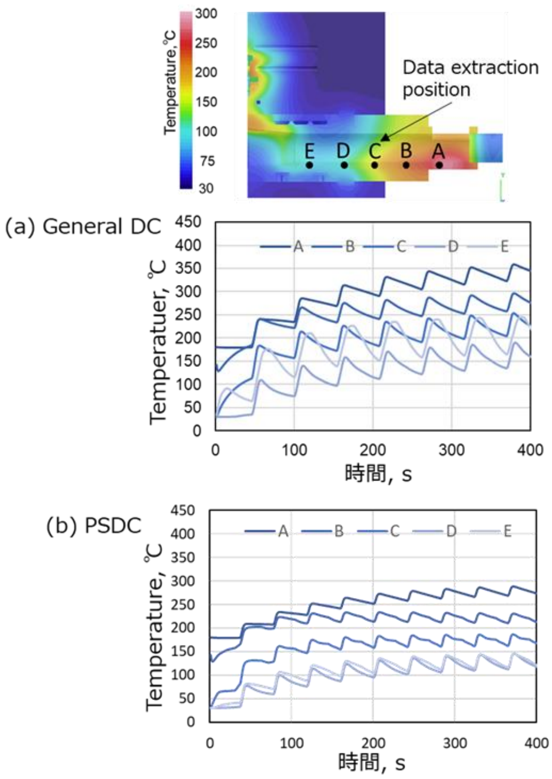

Fig. 8: Comparison of simulated temperature distributions across sleeve cross-

Figure 9 shows the temperature variation at five cross-sectional points (A–E) from the sleeve inlet to the biscuit region over the first ten cycles from a cold start. In both the general DC and PSDC cases, a relatively uniform temperature gradient was observed from point A near the sleeve inlet to point D near the biscuit.

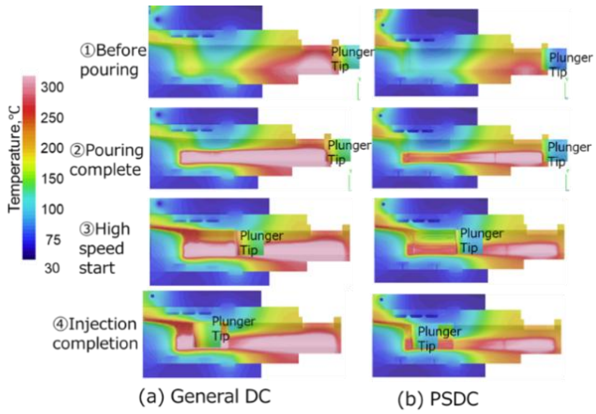

Fig. 9: Temperature variation across sleeve sections over multiple shots.

However, the general DC condition resulted in a large temperature rise throughout the sleeve and significant temperature fluctuation per cycle. On the other hand, in the PSDC process, the temperature rise beneath the sleeve inlet was effectively suppressed, leading to notably smaller thermal fluctuations within each casting cycle.

5.3 Stabilization of Die Temperature

In the PSDC process, the molten metal temperature and biscuit thickness are both reduced, which lowers the total heat input into the die. At the same time, the stabilization of the injection mechanism and the shortened curing time allow the cycle time to be reduced. To assess the impact of cycle time shortening on die temperature stabilization, temperature variations on the die surface were analyzed over one casting cycle. The results are shown in Figure 10.

The evaluation point corresponds to the red-marked region on the product, and temperature changes of the associated surface mesh element were tracked.

In PSDC condition, the die temperature at the end of the cure phase reached 216 °C for the fixed die half, with a fluctuation a of 158 °C, and 163 °C for the moving die half, with a fluctuation b of 145 °C. In comparison, under the general DC condition, the fixed die half had a final temperature of 178 °C with a 170 °C fluctuation c, and the moving die half reached 128 °C with a fluctuation d of 205 °C. These results indicate that, even when the molten metal temperature is reduced to lower the heat input, the die temperature can be kept higher and more stable during filling by shortening the cycle time.

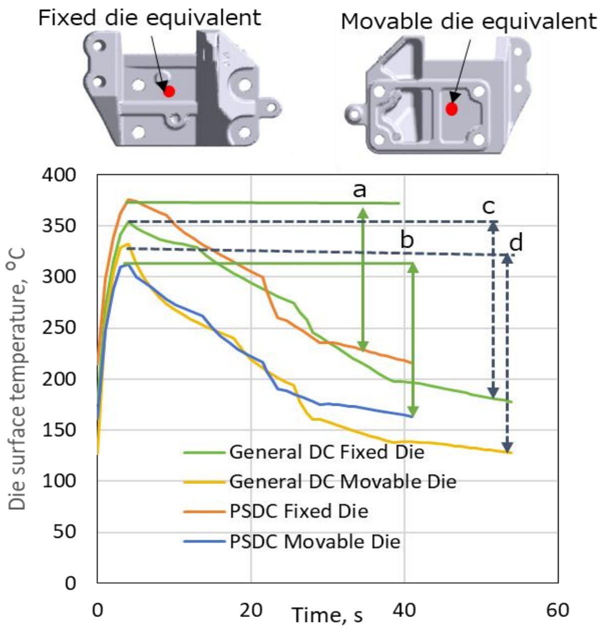

Fig. 10: Die surface temperature fluctuation during one casting cycle.

6. Validation of Solid Fraction in the Sleeve

The temperature distribution of the injection section calculated in Section 4 was mapped onto the model shown in Figure 4(b). Based on this mapping, the solid fraction distribution of the molten metal in the sleeve at the end of ladle pouring was computed using the model illustrated in Figure 4(a). Figure 11 shows the temperature distribution of the die and injection area cross-section, as well as the corresponding solid fraction distribution of the molten metal inside the sleeve at the start of injection.

In the general DC condition, only a small amount of solid phase was observed near the biscuit area, with no significant solidification occurring elsewhere. In contrast, under the PSDC condition, the molten metal exhibited solidification throughout the sleeve, forming a broad solid–liquid coexistence region.

To quantitatively evaluate the proportion of solid within the molten metal, the volume of iso-surfaces at a given solid fraction fs (denoted Vfs was calculated, and the ratio to the total molten metal volume Vall was determined using the relationship Ratio=V_{f_s}/V_{al} .)

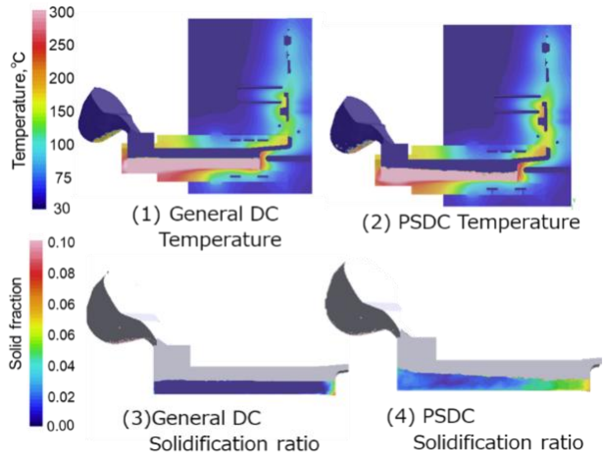

Fig. 11: Die temperature distribution and solid fraction in sleeve at the start of filling.

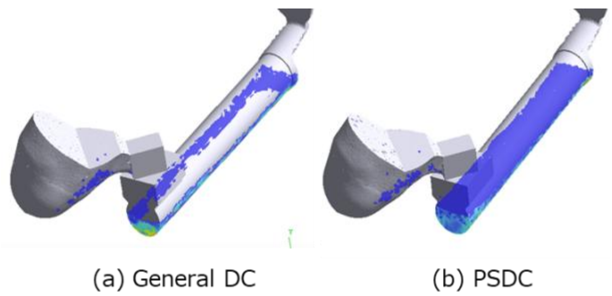

Fig. 12: Iso-surface comparison at a solid fraction of 0.01.

Figure 12 illustrates the isosurface extracted at fs=0.01 For this very low solid fraction, the general DC condition showed partial solid layers along the sleeve surface (skin layer formation).

In contrast, under the PSDC condition, approximately 73% of the molten metal volume was in a solid–liquid coexistence state, indicating widespread dispersion of nucleated crystals. Figure 13 presents the relationship between the solid fraction fs and the corresponding iso-surface volume ratio (Ratio) in both the general DC and PSDC conditions.

In the PSDC case, the Ratio at fs=0 was zero, indicating that a fully liquid state did not exist. At fs=0.0005, the Ratio reached 1, suggesting that nearly the entire molten metal volume contained extremely fine nuclei—preliminary stages of Al-α crystal growth—dispersed throughout the molten metal.

At f_s=0.05, the isosurface volume ratio in both the general DC and PSDC conditions approached zero, confirming that the PSDC process successfully controlled the solid fraction below the threshold target of 0.05.

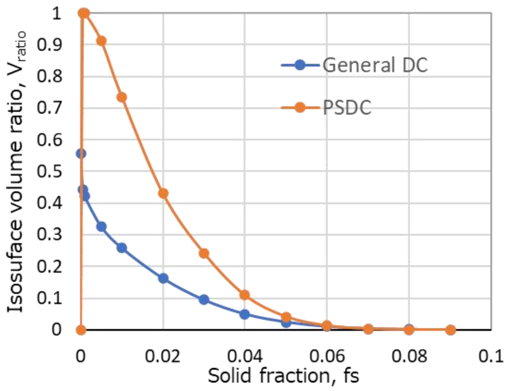

Fig. 13: Relationship between solid fraction and isosurface volume in the sleeve molten metal.

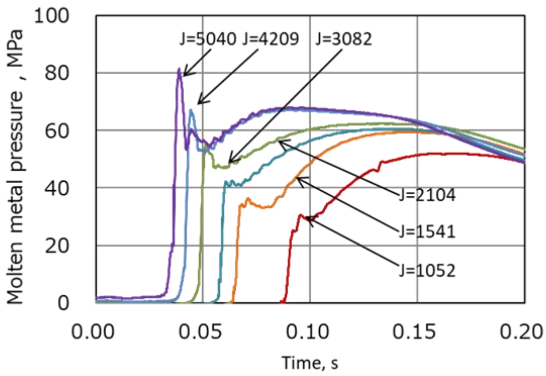

Fig. 14: Comparison of isosurface volume ratios between uniform and full-model sleeve temperature simulations.

Additionally, Figure 14 compares the isosurface volume ratios calculated under two conditions: (1) assuming uniform sleeve temperatures ranging from 150 °C to 250 °C, and (2) using the full model with spatially variable sleeve temperature distributions.

As shown earlier in Figure 9, there is a pronounced longitudinal temperature gradient within the sleeve. Therefore, assuming a uniform sleeve temperature leads to discrepancies in regions where the actual distribution diverges significantly from the assumed value. In fact, the full model calculation produced a higher Vfs than the constant 150 °C temperature case.

These findings indicate that accurate quantification of solid fraction distribution in the sleeve requires full-model calculations that account for realistic, spatially variable temperature distributions.

7. Verification of Increased Internal Pressure in the Product

In die casting, increasing the gate velocity reduces the molten metal filling time in the cavity. Figure 15 shows an example of measured cavity pressure profiles during such rapid filling [7]. The pressure waveforms are categorized according to J-Factors, which are determined by gate geometry and gate velocity, allowing comparison across different product types. When the J-Factor increased from 1052 to 1520, both the initial molten metal pressure and the peak casting pressure increased.

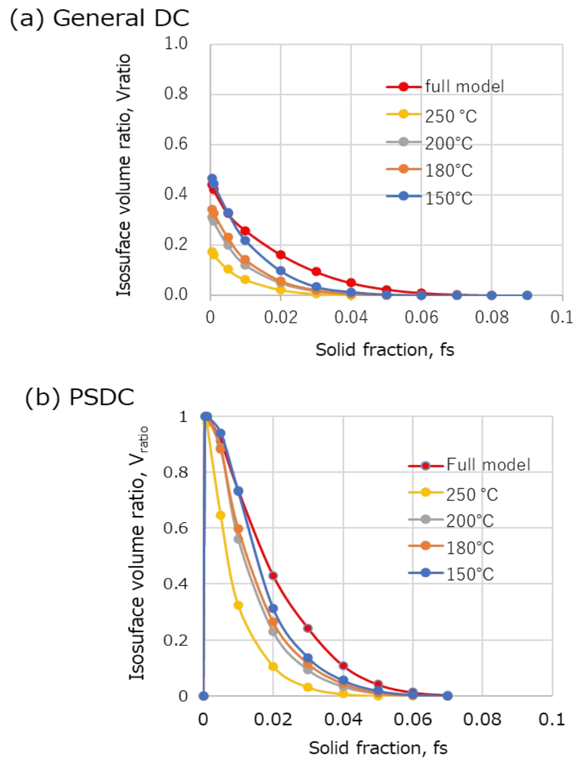

Fig. 15: Measured product pressure during filling and its relation to J-Factor [7].

Based on these results, the internal pressure of the product under both PSDC and general DC conditions was simulated. The results are shown in Figure 16, and Table 2 summarizes the molten metal pressure and solid fraction in the biscuit area and thick section of the product. Under the general DC condition, no solid phase was observed in the stamp section. In contrast, PSDC exhibited a solid–liquid coexistence state, and the molten metal pressure was approximately 60% higher than in the general DC condition. In the thick section of the product, the general DC condition showed a higher solid fraction (0.047) due to lower die temperature. However, the molten metal pressure in the PSDC condition was approximately 50% higher. This pressure increase is consistent with experimental observations where the pressure intensification time was shortened from 50 ms to 45 ms. It is considered that the reduction of porosity in thick sections is partially attributable to this increase in molten metal pressure.

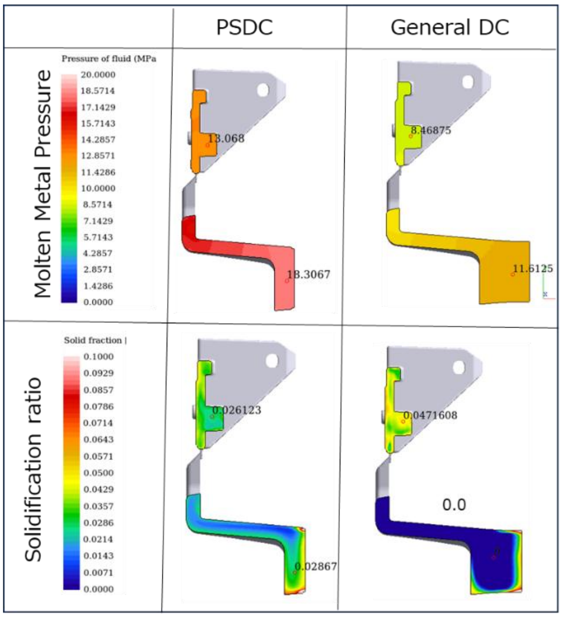

Fig. 16: Comparison of molten metal pressure and solid fraction distribution between general DC and PSDC.

Table 2: Molten metal pressure and solid fraction in different regions of the cast product.

		Solidification ratio	Molten Metal Pressure	PSDC to General DC Ratio
Biscuit area	PSDC	0.029	18.3	1.6
	General DC	0.000	11.6	
Thick section	PSDC	0.026	13.1	1.5
	General DC	0.047	8.5	

8. Verification of Porosity Reduction in Thick Sections

Finally, the reproducibility of porosity generation in thick sections was verified through simulation. In the PSDC process, die temperatures are higher than in the general DC condition. Therefore, conventional porosity prediction methods based on the cooling rate gradient of the product may not be suitable for evaluating PSDC.

To address this, the effect of increased nucleation in the molten metal under the PSDC condition was investigated using the porosity prediction algorithm implemented in CAPCAST. The porosity calculations were based on a solidification model proposed by Kubo, which considers dendrite growth and pore nucleation during solidification [8]. The simulation also included pressure analysis that accounts for delay in pressure intensification.

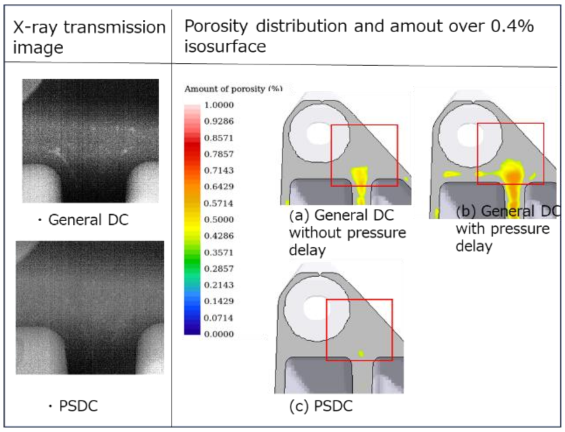

Fig. 17: Porosity distribution comparison at the 0.4% isosurface threshold.

Figure 17 shows a comparison of porosity distribution results extracted at an isosurface threshold of 0.4% porosity volume fraction.

Under the general DC condition, simulations that did not consider pressure delay underestimated porosity compared to experimental results. However, when the pressure delay was included, the simulated porosity distribution matched well with X-ray transmission images.

It should be noted that X-ray irradiation was performed at an oblique angle to the viewing plane, and therefore porosity in vertical ribs may not appear clearly in the radiographic images.

In the PSDC condition, the isosurface representing 0.4% porosity volume fraction was virtually absent, indicating minimal porosity. This result closely matched the experimental observations.

The simulation demonstrated that dispersed micro-scale solid fractions in the molten metal under PSDC conditions play a critical role in suppressing porosity formation in thick sections, confirming the effectiveness of the process through numerical analysis.

9. Discussion

The target product in this study is subjected to extremely severe thermal conditions, where molten metal exceeding 600 °C is introduced into the injection system within a short period of 6 to 10 seconds, and rapid acceleration of the molten metal is required within that timeframe. Consequently, stable operation of the injection mechanism demands advanced management and precise design. Conventionally, attempts to stabilize the casting process by lowering the molten metal temperature have faced challenges due to the occurrence of Cold Flake, making practical implementation difficult. However, in this study, by fully utilizing the capabilities of CAE and constructing a comprehensive model that includes the injection mechanism, coupled fluid flow and heat transfer simulations were performed. These simulations visualized the temperature distribution and low solid fraction state within the sleeve, revealing that stable casting is achievable without the formation of fractured Cold Flake.

Moreover, full-model analysis that incorporates complex conditions—such as molten metal behavior during ladle pouring and the changing boundary conditions associated with plunger tip movement—is technically demanding. Except for a few studies involving deformation analysis of the sleeve [9], such comprehensive simulations are rarely reported. Nonetheless, recent advances in particle-based methods for detailed analysis of molten metal behavior in sleeves [10,11] suggest that higher-precision thermal analysis will play an increasingly important role in the future.

10. Conclusion

This study proposed a novel Partial Solid Die Casting (PSDC) process, which aims to significantly reduce energy consumption during production while improving product quality in thick sections, achievable using standard die casting equipment. Through comprehensive CAE analysis including the ladle pouring and injection systems, the following findings were obtained:

1.In the PSDC process, appropriate control of molten metal temperature enables the solid fraction in the injection sleeve to be kept below 0.05.

2.The molten metal in the sleeve under PSDC conditions contains finely dispersed crystal nuclei with a solid fraction of approximately 0.0005 to 0.001, suggesting a solid–liquid coexisting state prior to significant dendritic growth.

3.Despite higher die temperatures in the PSDC condition, the porosity volume fraction in thick sections was reduced. This is attributed to the presence of fine, dispersed nuclei that suppressed the initiation and growth of porosity.

4.Increasing the J-Factor during gate passage resulted in higher molten metal pressure at the end of filling, further contributing to porosity reduction.

11. Acknowledgements

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Conflicts of interest:

Authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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