Research Papers

Development and Practical Application of ADC12 Aluminum Alloy Semi-Solid Die Casting Mass Production Technology Using Mechanical Vibration

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Abstract

The semi-solid die casting method has advantages such as reduction of casting defects and improvement of dimensional accuracy. On the other hand, ADC12 alloy, which is widely used as a die casting alloy, is difficult to be used for semi-solid die casting because of its narrow temperature range which is suitable for semi-solid slurry formation. In this development, ADC12 alloy slurry was successfully formed by applying mechanical vibration to the cooling process from the molten state to the solid-liquid coexistence temperature and optimizing the conditions. In addition, this technology was realized in the mass production process, and it was adopted for hydrogen supply unit components used in FCEV (Fuel Cell Electric Vehicle).

1. Introduction

Amid the growing need for carbon neutrality in the automobile industry, there has been an increased demand for high-quality, lightweight, and cost-effective aluminum raw materials.

Figure 1 Relation between costs and quality

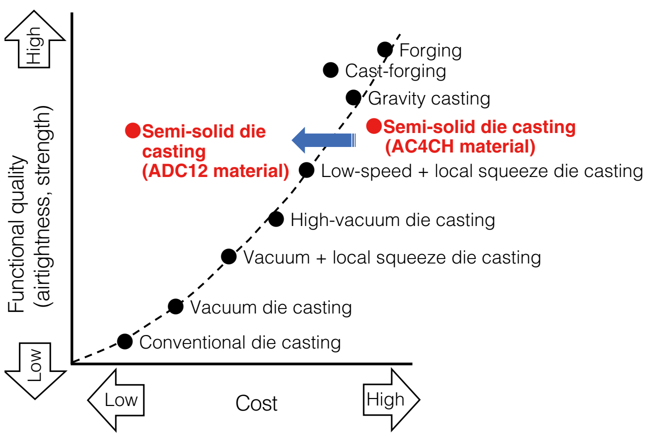


Figure 1 shows a correlation curve between functional quality and costs for a method of producing aluminum raw materials, illustrating a relationship in which an increase in functional quality leads to higher costs.

In conventional semi-solid die casting (DC), AC4CH aluminum alloy materials have generally been used. However, these materials have the following drawbacks that contribute to high costs:

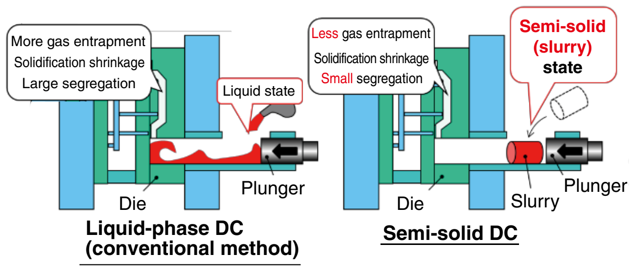
- Low market distribution volume, leading to high material costs;
- Low fluidity, resulting in large wall thicknesses depending on the shape;
- Low mechanical properties, requiring post-processing such as heat treatment based on quality requirements.

Thus, development was carried out to use ADC12 aluminum alloy materials, which have large market distribution and are commonly used in relatively inexpensive die casting, for semi-solid die casting. This approach achieves both high-quality and cost-effective aluminum rough shape materials, ultimately meeting market demands.

2. Characteristics of Semi-Solid DC

In general, in liquid-phase die casting, rippling of the liquid traps air, as shown in Figure 2, and the transition from the liquid to solid phases causes the material to shrink.

Figure 2 Differences between liquid-phase and semi-solid die casting



These phenomena cause porosity due to air entrapment and shrinkage, as well as segregation of alloy compositions caused by rapid cooling. These factors reduce internal quality and are inevitable issues associated with high-speed molding of liquid metal.

In contrast, semi-solid die casting uses a slurry in which metal is in a semi-solid state at a temperature lower than that of liquid-phase die casting. Therefore, semi-solid die casting is expected to reduce coagulation shrinkage and porosity, as well as improve dimensional reproducibility.

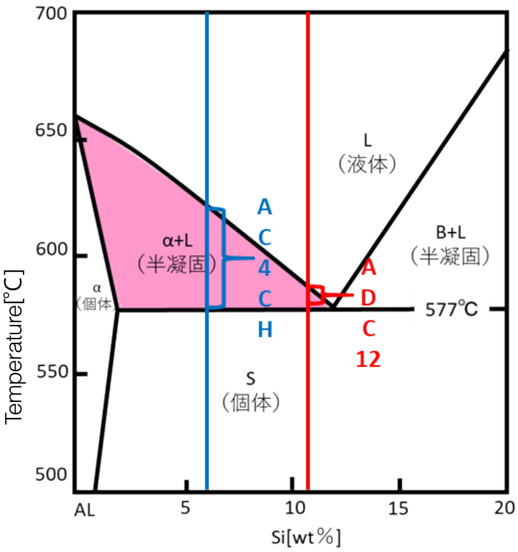
Additionally, semi-solid die casting can help reduce porosity by preventing air entrapment, as there is no rippling during injection when the plunger starts to move.

Furthermore, since the material filling the mold is in a slurry state with a relatively uniform metallographic structure, semi-solid die casting is expected to reduce segregation and fluctuations in mechanical properties, thereby improving the mean values of these parameters.

Therefore, semi-solid die casting is considered a fundamental solution to the problems involved in conventional die casting of liquid metal. However, it also has some disadvantages.

The first disadvantage is the risk of underfill due to the reduced fluidity caused by pouring a high-viscosity fluid into a mold.

Figure 3 AL-Si binary state diagram



The second disadvantage is the challenges associated with the material characteristics of ADC12 when applied to die casting.

As shown in the state diagram in Figure 3, ADC12 has a smaller temperature range where the material can exist in a solid-liquid coexistence state compared to AC4CH. This makes it more difficult to control the temperature and produce a semi-solid metal slurry.

Additionally, as shown in Figure 4, ADC12 and AC4CH exhibit different coagulation patterns. AC4CH coagulates uniformly in a gruel-like state, while ADC12 coagulates from the peripheral sections, where the temperature decreases faster than in other areas. This can lead to an uneven solid phase ratio within the slurry and result in segregation. Therefore, although ADC12 is low in cost and high in strength, it has been considered a material that is difficult to use for producing high-quality semi-solid slurry with a uniform solid phase.

3. Producing the Semi-Solid Slurry of ADC12 Alloy

In the production of the ADC12 alloy slurry, molten metal is poured into a container, which is mechanically vibrated at a temperature lower than that of the molten metal. The metal is then cooled while being circulated by convection, reaching a solid-liquid coexistence state.

When molten metal is cooled, a solid phase precipitates on the surface of the container, which is at a lower temperature than that of the molten metal.

Figure 4 Image showing the difference in coagulation by alloy

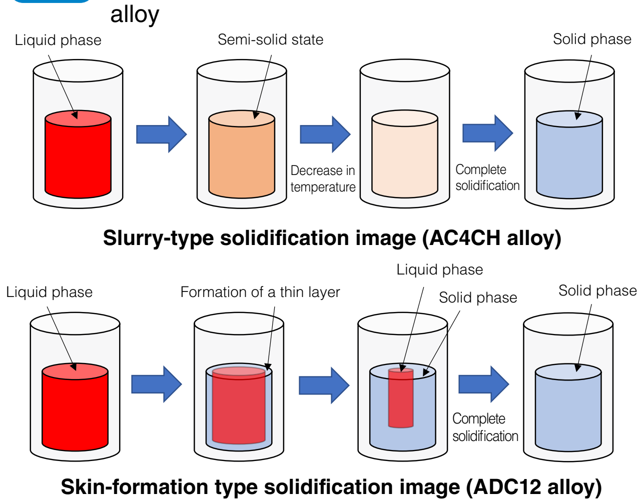


Figure 5 Conceptual image of slurry production

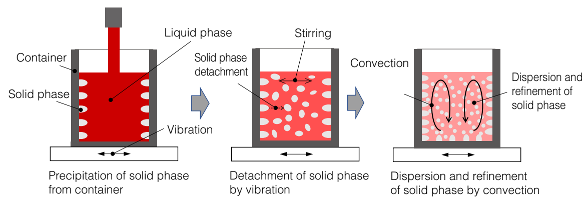
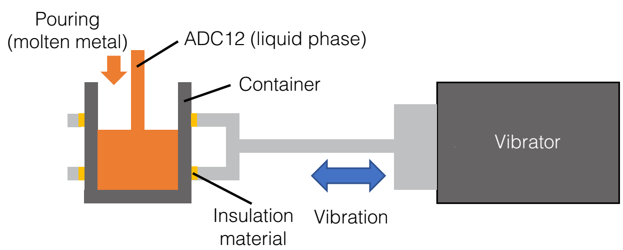


Figure 6 Conceptual image of mechanical vibration device



A conceptual image of this process is shown in Figure 5.

Conventionally, AC4CH slurry has been produced by causing molten metal to flow in a rotational direction, such as with electromagnetic stirring, which disperses and refines the solid phase that precipitates on the surface of the container. However, this method cannot produce a favorable ADC12 slurry, as a hard initial solidifying shell forms on the contact surface between the ADC12 and the container.

Therefore, to obtain a favorable ADC12 slurry, a strong stirring force through mechanical vibration is applied to the molten metal, which separates the solid phase from the surface of the container.

Figure 6 shows a conceptual image of a mechanical vibration device used to produce ADC12 slurry.

The device enhances the dispersion and refinement of the solid phase through convection, thereby equalizing the solid phase. In this way, a method has been established for producing high-quality slurry through the optimal application of mechanical vibration.

Figure 7 shows the effect of the slurry production method using mechanical vibration.

When no vibration was applied, a coarse structure

Figure 7 Observation of the structure of ADC12 alloy slurry

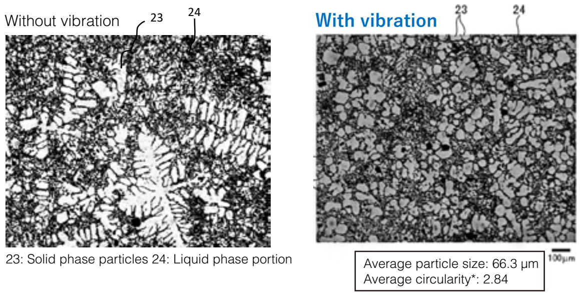
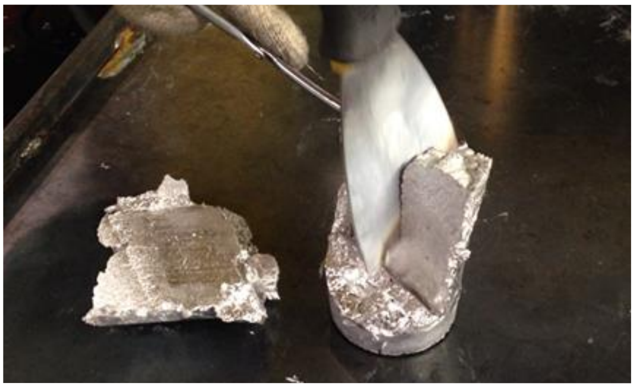


Figure 8 Observation of cutting ADC12 alloy slurry



growing into a dendrite-like form was observed. In contrast, when vibration was applied, the structure was refined and a favorable semi-solid slurry was obtainable in terms of the smallness of the mean particle size and the mean circularity of solid phase particles, which were considered to be ideal for maintaining the features of raw materials.

Additionally, the method was able to produce a slurry with uniform hardness from its surface to its interior, allowing it to be easily cut with a metal spatula. The cut section was smooth and clean (see Figure 8).

4. Challenges in Maintaining the Fluidity of the Slurry

Using a mold capable of producing a spiral test piece for evaluating flow lengths, the influence of shear stress on flow length was evaluated by varying gate thicknesses and injection speeds.

Using the spiral test piece shown in Figure 9, the relation between gate thickness and flow length was evaluated, as shown in Figure 10.

The flow length of ADC12 in a semi-solid state tends to increase as the gate thickness is reduced.

In the case of a gate thickness of 4.0 mm, the flow length was considered to have increased due to the decrease in flow resistance.

Next, the parameters used in the flow length test were reorganized using the following equations:

Shear rate: $\gamma = 6Q / (BH^2) = 6V / H$

(where γ is the shear rate, V is the gate speed, Q is the volume flow rate, B is the gate width, and H is the gate thickness), and

Shear stress: $\tau = \gamma \cdot \eta$

where η is the apparent viscosity.

Figure 9 Spiral test piece

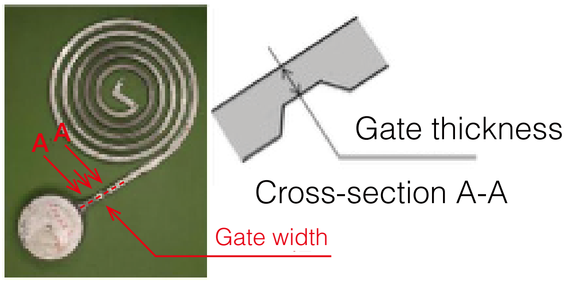
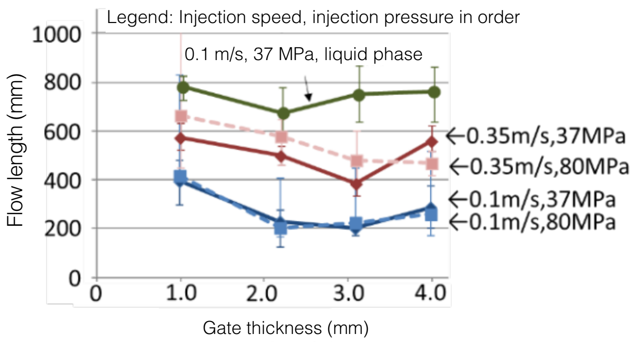


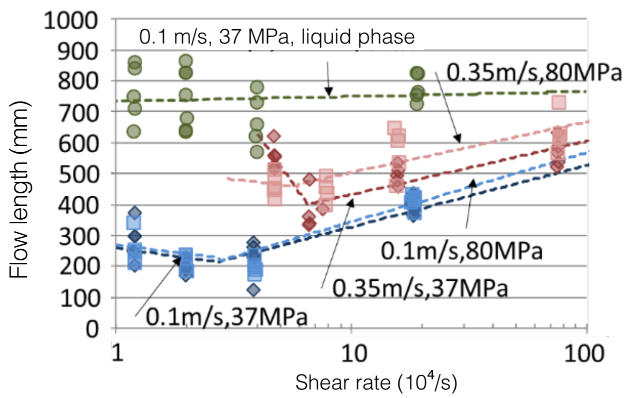
Figure 10 Relation between gate thickness and flow length



The shear rate increases as the gate width and thickness are reduced. Additionally, the shear rate increases as the gate speed is increased.

Figure 11 shows the reorganized relation between the calculated shear rates and flow lengths.

Figure 11 Relation between shear rates and flow lengths



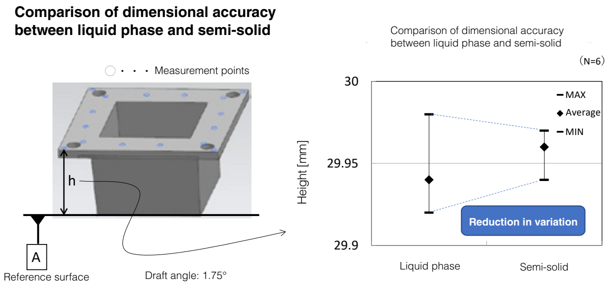
In a semi-solid state, the flow length is enhanced when the shear rate is increased above a certain amount. This suggests that the slurry fluidity improves due to the reduction in slurry viscosity when the shear rate at the gate is increased, causing the slurry to experience greater shear stress.

Accordingly, it was confirmed that applying a certain level of shear rate allows a flow length similar to that of the liquid phase to be maintained.

5. Dimensional Accuracy and Mechanical Properties

The influence of phase differences on dimensional accuracy was evaluated by comparing the products shown in Figure 12, which were produced through liquid-phase and semi-solid die casting.

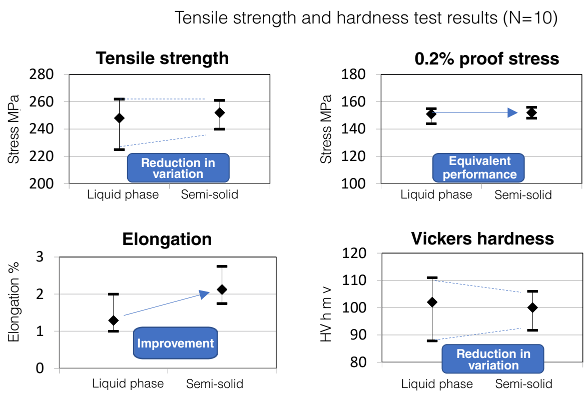
Figure 12 Comparison of dimensional accuracy between liquid-phase and semi-solid die casting



The product produced through semi-solid die casting exhibited reduced dimensional variation compared to the product produced through liquid-phase die casting. This suggests that the smaller shrinkage rate in semi-solid die casting, compared to liquid-phase die casting, contributed to the improvement in dimensional reproducibility.

Next, mechanical property tests were conducted using test pieces (ϕ10) produced through liquid-phase and semi-solid die casting. The results of the comparative evaluation of the mechanical properties are shown in Figure 13.

Figure 13 Mechanical properties of liquid-phase and semi-solid die casting



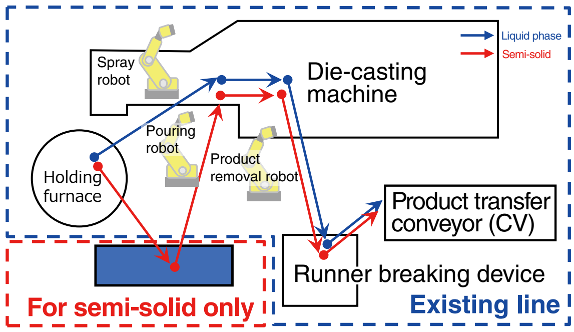
The test piece produced through semi-solid die casting exhibited improved elongation compared to the one produced through liquid-phase die casting, with equivalent properties for the other test parameters. This suggests that the application of vibration contributed to a more uniform refinement of the structure, resulting in less segregation and, consequently, reduced variation and improved stability.

6. Establishing a Common Line for Liquid-Phase and Semi-Solid Die Casting

Figure 14 shows the common line established by Aisan Industry for both liquid-phase and semi-solid die casting.

The area surrounded by dotted lines represents the existing die casting line, while the area surrounded by solid lines represents the process line exclusively for producing semi-solid slurry. In semi-solid die casting, the exclusive process line is fully automated, with robotic transport used for cooling the container,

Figure 14 Overview of the line



applying a mold release agent to the container, producing slurry through vibration, and performing other processes.

In this way, establishing a common line has contributed to a reduction in investment and allowed production facilities to be effectively utilized according to production loads, thereby reducing costs.

7. Effects of the Development

Lastly, the effects of the development are summarized, as shown in Figures 15 and 16.

The first effect is the improvement of internal quality. Semi-solid die casting can reduce the void ratio to one-tenth of that in liquid-phase die casting. It was confirmed that semi-solid die casting helps reduce porosity, an internal defect, by preventing air entrapment and shrinkage, which are key characteristics of

Figure 15 Improvement in internal quality

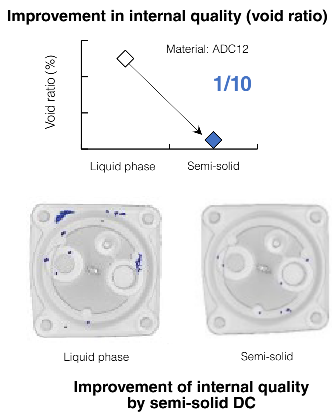
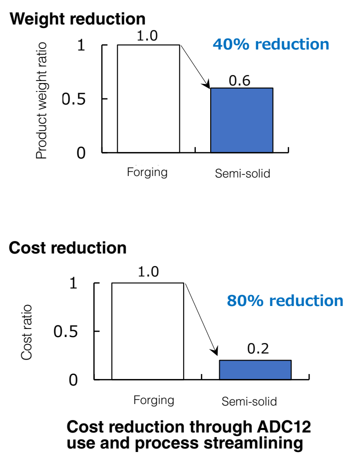


Figure 16 Downsizing and cost reduction effects



this casting method.

The second effect is the facilitation of downsizing. Semi-solid die casting achieves approximately 40% reduction in weight compared to conventional forged components by ensuring fluidity and achieving near-net-shape production, similar to products made through liquid-phase die casting.

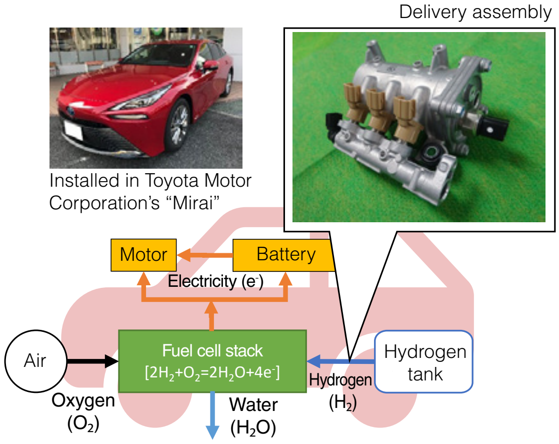
The third effect is cost reduction. Establishing a common line for liquid-phase and semi-solid die casting using ADC12 has reduced production costs by approximately 80% compared to forging. Additionally, using ADC12 can eliminate the need for T6 treatment, thereby contributing to a reduction in CO_2 emissions.

8. Conclusion and Future Actions

This development achieved the successful production of a semi-solid slurry of an alloy like ADC12, with a composition close to the eutectic point, which has been considered difficult. The developed technology for producing semi-solid slurry is now available for most alloys.

By using this technique and receiving significant cooperation from the individuals involved, we have achieved mass production of the second-generation hydrogen delivery assembly for FCVs (see Figure 17).

Figure 17 Hydrogen delivery assembly for fcvs



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Award-Winning Achievements

FY2021

Aichi Invention Commendation: Aichi Invention Award (Aichi Prefecture Invention Association, a General Incorporated Association)

Chubu Region Invention Commendation: Invention Encouragement Award (Japan Institute of Invention and Innovation, a Public Interest Incorporated Association)

FY2023

Japan Foundry Engineering Society: Toyota Award (Japan Foundry Engineering Society, a Public Interest Incorporated Association)

Sokeizai Industry Technology Award: Encouragement Prize (SOKEIZAI Center, a General Incorporated Association)

Chubu Science and Technology Center Commendation: Promotion Prize (presented by the Public Foundation of Chubu Science and Technology Center, a Public Interest Incorporated Association)