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A new slurry-making method, called the nucleation-accelerated semi-solid slurry (NASS) method, was developed to fabricate high-quality semi-solid slurry with fine and uniform globular microstructures. The method’s application to rheo-diecasting of ADC10 alloy was investigated. To enhance the heterogeneous nucleation of primary α particles in the initial stage of solidification, various types of funnels, including the pouring system in the slurry-making vessels, were designed and estimated by thermal analysis. It was found that the heterogeneous nucleation of primary α particles was closely related to the temperature–time history and the flow pattern. In the present study, the NASS method was set up based on the optimized funnel. It consisted of a specially designed conical-shaped funnel and the electromagnetic stirring (EMS) unit for artificial agitation. The conical-shaped funnel generated swirly flow pattern in the melt. This was further exaggerated by the EMS in the slurry-making vessel during the pouring stage, resulting in a copious heterogeneous nucleation. The qualities of the slurry were investigated using optical microscopy and rheo-diecasting. To study the effect of process parameters, the semi-solid slurry of ADC10 alloy was rheo-diecast using an 85-ton high-pressure die casting (HPDC) machine. Microstructural observation and hardness test were then carried out on the rheo-diecast specimens. The rheo-diecast products of the NASS method showed fine and uniform microstructures, with primary α-globules diameter averaging 39 μm and form-factor indicating a degree of globularity of 0.9. The optimized heat treatment condition for the rheo-diecast product of ADC10 alloy was achieved at the solution temperature of 490°C for 30–60 min, water quenching, and age hardening at 180°C for 7–8 h.

KEY WORDS: semi-solid; rheocasting; rheo-diecasting; thermal analysis; nucleation; electromagnetic stirring; ART (advanced rheocasting technology); ADC10 alloy; hardness; heat treatment.

1. Introduction

During the last decade, the demand for high energy efficiency and low exhaust emission in the automotive industry has steadily increased.1) The conventional parts of automobiles based on heavy materials, such as cast iron and steel, have been replaced with lightweight parts of aluminum alloys. High-pressure die casting (HPDC) has become a representative casting method for manufacturing aluminum components, owing to its high productivity and dimensional accuracy. Many components, such as air compressor, gear box, and gasoline engine block, are being successfully produced via HPDC using ADC10 (Al9Si3Cu) alloy. ADC10 is a major alloy since it has good castability resulting from its narrow solidification range. This processing has some limitations, however, with regard to obtaining proper mechanical properties. Feeding defects (e.g., blow holes and scattered chills) and inner defects (e.g., gas porosities and shrinkage cavity), attributed to the turbulent flow patterns and the high pouring temperature in the HPDC processing, are the main causes of deterioration of mechanical properties. Heat treatment is generally carried out to improve the mechanical properties of aluminum alloys. However, in the case of HPDC components, the improvement of mechanical properties through heat treatment cannot be expected. This is because the aforementioned defects lead to some problems such as blisters and plastic deformation during the solution treatment. In this context, rheocasting can be applied in place of HPDC with ADC10 alloy for high-strength aluminum components.2) It is an attractive processing method, since a semi-solid slurry achieves laminar flow and a lower volume of gas content.3) Rheocasting is effective in reducing the formation of porosities in the castings because of low gas content in the slurry and low pouring temperature. Therefore, the integral microstructure of the rheocast products enables heat treatment including solution treatment and artificial aging, which leads to improved mechanical properties.4) One of the most important considerations in rheocasting is how to obtain a high-quality semi-solid slurry, which consists of fine and uniform globular α-particles surrounded by liquid at an appropriate ratio at temperature ranges for the semi-solid state. There are two typical semi-solid slurry-making methods, according to the mechanism of globular microstructure evolution: (i) the dendrite fragmentation mechanism and (ii) the nucleation mechanism. The methods based on the nucleation mechanism have now been considered as the more efficient ones compared to the
other methods. In the case of ADC10 alloy, it is generally considered difficult to make the semi-solid slurry without sufficient nucleation in the early stage of solidification, since it has a narrow mushy region owing to its nearly eutectic composition.

Several methods based on the nucleation mechanism were recently developed with A356 (AlSi2.5Mg) alloy. These methods include the New Rheocasting (NRC) process, the Semi-solid Rheocasting (SSR) process, and the Advanced Semi-solid Casting Technology (ASCT). The basic concepts of these methods can be summarized as follows:
- The pouring temperature should be kept as low as possible to prevent the remelting of α particles.
- After the pouring stage, a stirring rod or a cooling pipe is used to enhance the nucleation of α particles.
- To reduce the temperature difference between the surface and the center of the slurry, mechanical agitation is involved during the cooling stage, which leads to an increase in the globularity.

In the case of ADC10 alloy, the range of the mushy zone—which refers to the temperature difference between the liquidus and the solidus temperatures—is very short compared to A356 alloy. It is very difficult to have sufficient α nuclei in the melt during the initial stage of solidification, to form proper semi-solid slurry for rheocasting. In order to obtain proper semi-solid slurry for rheocasting of ADC10 alloy, nucleation of α particles must be increased, resulting in a slurry with fine and uniform globular α particles. According to previous works, the quality of the semi-solid slurry is closely related to the density of α particles, i.e., the number of α nuclei (or particles), which is determined by the heterogeneous nucleation in the initial stage of solidification during the pouring of the melt.

In the present study, the main target was to develop a new method by which the heterogeneous nucleation of α particles can be greatly enhanced in order to fabricate high-quality semi-solid slurry with fine and uniform globular microstructures for rheocasting of ADC10 alloy. The slurry-making technique adopted by the authors was such that the main sites of heterogeneous nucleation of α particles were on the surface of the slurry-making vessel. In this technique, activating the nucleation condition along the contact area of the melt and the wall of the slurry-making vessel is very important. When a liquid metal is poured into a slurry-making vessel, it initially contacts with the funnel surface and then finally with the vessel wall. To study the effect of the funnel type on the heterogeneous nucleation of α particles and the quality of the slurry, various types of funnels were designed and estimated. The qualities of the slurry made through various methods were investigated using optical microscopy, and rheo-diecasting using the slurry obtained was carried out using the ART (Advanced Rheocasting Technology) system. Heat treatment was also carried out on the rheo-diecast specimens and the hardness of the specimens was measured to estimate the quality of the rheocast products.

2. Experimental Procedure

The chemical composition of the commercial ADC10 alloy used in the present study is shown in Table 1. The composition of ADC10 alloy, which is close to the eutectic, does not seem responsive to the thermodynamic criterion for semi-solid processing. The criterion was originally suggested to evaluate the applicability of alloys for thixoforming. According to the previous study, however, this criterion can also provide some valuable information for rheocasting.

ADC10 alloy was melted and degassed at 700°C using pure argon gas with a degassing chemical tablet (N₂) injected into the melt, and held at 660±5°C for slurry making. To estimate the effect of nucleation on the quality of semi-solid slurry, various kinds of nucleation conditions were tested. Figure 2 illustrates four kinds of slurry-making systems used in the present study, which might lead to different nucleation effects: (a) liquidus casting (Method-A), (b) liquidus casting with a vertical-shaped funnel (Method-B), (c) artificial agitation using EMS with a verti-

### Table 1. Chemical composition of ADC10 alloy (wt%).

<table>
<thead>
<tr>
<th>Composition</th>
<th>Cu</th>
<th>Si</th>
<th>Mg</th>
<th>Fe (wt%)</th>
<th>Mn (wt%)</th>
<th>Ni (wt%)</th>
<th>Ti (wt%)</th>
<th>Al (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC10</td>
<td>2.5–3.5</td>
<td>7.5–9.5</td>
<td>0.25–0.45</td>
<td>&lt;0.9</td>
<td>&lt;0.1</td>
<td>&lt;0.05</td>
<td>&lt;0.2</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Fig. 1. The relationship of temperature versus solid fraction in ADC10 alloy, indicating the thermodynamic values calculated by Thermo-Calc.
cal-shaped funnel (Method-C), and (d) the nucleation-accelerated semi-solid slurry-making (NASS) method consisting of the EMS unit for artificial agitation and a specially designed conical-shaped funnel (Method-D). The slurry-making vessel was made of stainless steel φ50 mm in diameter and 100 mm in length, and the inner surface was coated with BN₂. The funnel applied for Method-D was conical-shaped, in which the melt flows spirally along the inner surface of the funnel into the slurry-making vessel during the pouring stage. Compared to the vertical-shaped funnel, the contact time of the melt with the inner surface of the conical-shaped funnel increases, leading to enhanced heterogeneous nucleation of the primary α particles. Furthermore, when the spirally agitated melt flows into the slurry-making vessel, the melt will be agitated further by the EMS set around the vessel. This leads to uniform temperature and solute distributions, thus preventing the formation of initial solidification shell on the inner surface of the vessel.

The experimental conditions for slurry making are shown in Table 2. The pouring temperatures of the melt ranged between 600°C and 650°C. The semi-solid slurries were taken out of the slurry-making vessel at 590°C and rheo-diecast using an 85-ton HPDC machine. The solid fraction at this temperature was estimated at 0.15 by Thermo-Calc.

For the microstructural observation, all the samples were ground with SiC papers and polished on a cloth with a 0.04 μm diamond suspension. The microstructures were analyzed using an optical microscope fitted with a digital camera and an image analyzer. The solute distribution was investigated using electron probe microanalysis (EPMA). Heat treatment was carried out on the rheo-diecast test specimens and the hardness was measured using a Rock-

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**Table 2.** Summary of the slurry-making methods and process conditions.

<table>
<thead>
<tr>
<th>Slurry making method</th>
<th>Funnel type</th>
<th>Agitating speed by EMS (rpm)</th>
<th>Pouring temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method-A</td>
<td>-</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Method-B</td>
<td>vertical-shaped</td>
<td>0</td>
<td>ranged between 600°C and 650°C</td>
</tr>
<tr>
<td>Method-C</td>
<td>vertical-shaped</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Method-D</td>
<td>conical-shaped</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>
well hardness tester (HRS-150) to investigate the effect of the slurry microstructure on mechanical properties.

3. Results and Discussion

3.1. Microstructural Characteristics of the Semi-solid Slurry

It is well known that the evolution of solidification microstructures of alloys is closely related to the thermal history of the liquid metal during the nucleation and growth stage. Especially, in the case of semi-solid slurry making, the nucleation of the primary $\alpha$ particles plays a key role in determining the microstructural evolution and quality of the slurry.

Quantitative analyses of the mechanism of nucleation have been reported using X-ray observation of non-organic materials or polymers with low melting point. However, in cases of metallic alloys, direct observation is very limited, thus the thermal analysis using the cooling curve experiment has been widely applied in evaluating the nucleation and growth characteristics in alloy solidification. The representative points in the cooling curve experiment are suggested as follows

- $T_{\text{NUC}}$: the nucleation temperature;
- $T_{\text{MIN}}$: the temperature point at which the latent heat caused by the phase transformation starts to become larger than the heat extracted from the mold wall (the minimum temperature after the start of solidification);
- $T_{\text{REC}}$: the recalescence temperature via the phase transformation (the maximum temperature after the start of solidification);
- $\Delta T_{\text{R}}$: the difference between $T_{\text{REC}}$ and $T_{\text{MIN}}$.

Figure 3 shows the temperature–time curve obtained by the cooling curve experiment using ADC10 alloy with a pouring temperature of 620°C for the case of Method-C in Fig. 2. The temperature variation with time was measured at two positions: one at the center and the other near the surface of the vessel. These are referred to as $T_{\text{cen}}$ and $T_{\text{sur}}$, respectively, as indicated in the figure. It is to be noted that both the extent of undercooling and recalescence near the surface region are much larger than those at the central region, and consequently, the value of $\Delta T_{\text{R}}$ is the amount of recalescence during solidification, i.e., $\Delta T_{\text{gap}}$.

Based on the cooling curve experiment as indicated in Fig. 3, two important parameters, $\Delta T_{\text{R}}$ and $\Delta T_{\text{gap}}$, are considered in relation to the final microstructures of semi-solid slurry. The basic concepts are: (i) the value $\Delta T_{\text{R}}$, which is closely related to heterogeneous nucleation, affects the size of $\alpha$ particles and (ii) the value of $\Delta T_{\text{gap}}$, which indicates the temperature uniformity in the melt, affects the uniformity of globular $\alpha$ particles of the semi-solid slurry. In order to obtain fine and uniform globular $\alpha$ particles in the semi-solid slurry, the values of $\Delta T_{\text{R}}$ and $\Delta T_{\text{gap}}$ should be kept high and low, respectively.

Two important processing parameters are considered in controlling the values of $\Delta T_{\text{R}}$ and $\Delta T_{\text{gap}}$: (i) the condition of agitation (stirring) in the melt and (ii) the pouring temperature. The condition of agitation of the melt during slurry making can be changed by using various slurry-making systems, as indicated in Fig. 2. The pouring temperature was changed to the 600°C and 650°C range. The temperature uniformity in the melt or the slurry is considered to be inversely proportional to $\Delta T_{\text{gap}}$. It is therefore reasonable to investigate the microstructural morphology of semi-solid slurry as functions of $\Delta T_{\text{R}}$ and $\Delta T_{\text{gap}}$ for various slurry-making conditions.

Figure 4 indicates the results of thermal analysis showing $\Delta T_{\text{R}}$ and $\Delta T_{\text{gap}}$ with various slurry-making methods and pouring temperatures. Here, the values $\Delta T_{\text{R}}$ are estimated based on $T_{\text{sur}}$ in the melt near the surface region since the heterogeneous nucleation in the vessel occurred mainly on the surface region. This is where the melt contacts with the vessel surface in the pouring stage. Therefore, the resultant recalescence is detected in the melt near the surface region. As shown in Fig. 4(a), as the pouring
temperature decreases, the value of $\Delta T_{\text{sur}}$ increases. This could indicate that the amount of heterogeneous nucleation increases as the pouring temperature decreases, leading to fine microstructures. It is also notable that the value of $\Delta T_{\text{gap}}$ decreases with the decrease of the pouring temperature, as shown in Fig. 4(b). The uniform temperature distribution in the melt may result in uniform microstructures, which will be discussed later. As shown in the figure, the values of $\Delta T_{\text{sur}}$ and $\Delta T_{\text{gap}}$ vary not only with the pouring temperature, but also with the slurry-making method adopted in the present study. The effect of the slurry-making method can be summarized by two important factors: (i) variation in the contact area (or time) between the melt and the inner surface of the slurry-making vessel including the funnel adopted and (ii) the stirring (or agitation) effect leading to turbulent mixing of the melt, i.e., uniform distributions of temperature and solute. As the slurry-making method changes from method-A, to -B, to -C and -D, both the contact area (or time) and the stirring effect increase. As mentioned previously, the contact area is related to the value of $\Delta T_{\text{sur}}$, i.e., the sites of heterogeneous nucleation; and the stirring effect is related to the value of $\Delta T_{\text{gap}}$, i.e., the temperature uniformity in the melt. Since method-D, compared to the others, has the largest contact area (or time) and the strongest stirring effect, it has the largest $\Delta T_{\text{sur}}$ and the smallest $\Delta T_{\text{gap}}$. It can be expected that method-D may result in more uniform and finer semi-solid microstructures. If there is no artificial stirring or agitation in the melt as in method-A or -B, the value of $\Delta T_{\text{sur}}$ will be small and the value of $\Delta T_{\text{gap}}$ will be large, resulting in small numbers of heterogeneous nucleation sites and large temperature difference in the melt. When method-A or -B is applied to ADC10 alloy, which has a composition near the eutectic with narrow mushy zone, proper semi-solid slurry for rheocasting cannot be obtained.

Figure 5 indicates the typical microstructures of the slurries obtained by various slurry-making methods, as shown in Fig. 2. In the cases of (b), (c), (d), and (e), the melt was poured in the slurry-making vessel at 620°C and then quenched into water at 590°C with a solid fraction of 0.15 to observe the slurry microstructures. Compared to the dendritic microstructure of diecasting shown in (a), the mi-
crostructures in (b) through (e) have rosette-like or globular \( \alpha \) particles with somewhat different morphologies. The microstructural characteristics, such as particle size, density, and the morphology of \( \alpha \) particles, are different from each other. Such differences are attributed to the different patterns of the cooling curves shown in Fig. 4. The slurries obtained by method-A and -B, in which no artificial agitation was added, have relatively small numbers of \( \alpha \) particles with the rosette-type morphology, as shown in (b) and (c). When the slurry was made with EMS, a globular microstructure was obtained owing to the uniform distributions of temperature and solute in the melt during the cooling stage, as indicated in (d). However, when the NASS method in Fig. 2(d) was adopted, a fine and uniform globular microstructure was obtained as shown in Fig. 5(e).

To evaluate the microstructure morphology of the slurry, quantitative parameters such as the particle size and the form factor were adopted using the following equations:

\[ D_e = \sqrt{4A/\pi} \quad \text{(1)} \]

and

\[ F = p^2/4\pi A \quad \text{(2)} \]

where \( D_e \) [\( \mu \text{m} \)] is the equivalent diameter (or the particle size) and \( F \) [dimensionless number] is the form factor indicating the index for the globularity of \( \alpha \) particles, respectively. \( A \) and \( p \) are the area and perimeter, respectively, of the particle. The results shown in Fig. 6(a) indicate the effect of the slurry-making methods on the size and morphology of \( \alpha \) particles. As described qualitatively in the microstructures shown in Fig. 5, the NASS method (method-D) indicates the finest particle size and highest globularity of \( \alpha \) particles. It was found that the swirly flow pattern of the melt caused by the conical-shaped funnel resulted in fine and uniform globular microstructure with the average \( \alpha \) particle size of \( 39 \pm 2 \mu \text{m} \). In the case of the liquidus casting showing the smallest \( \Delta T_{\text{LIC}} \) and largest \( \Delta T_{\text{PP}} \) as indicated in Fig. 4, the particle size of \( \alpha \) particles shows the largest, and the form factor the lowest values. The density of \( \alpha \) particles, which is defined as the number of \( \alpha \) particles in \( \text{mm}^2 \), was also estimated according to the slurry-making methods and is shown in Fig. 6(b). As the slurry-making method changes from method-A to -B, -C, and -D, the contact time of the flowing melt with the wall surface of the funnel and the vessel increases, leading to the increase of the density of \( \alpha \) particles.

In rheocasting, the uniformity of the slurry microstructure, which is closely related to the size and the density of \( \alpha \) particles, is important in determining the mechanical properties of the final cast products. In Table 3, the quantitative analysis of the representative microstructures is summarized for the four kinds of slurry-making methods, including the analysis of the uniformity of \( \alpha \) particles. The distribution of \( \alpha \) particles was analyzed using an estimation index called the Mean Distance between the Particles (MDP).\(^{21}\) The standard deviation (S.D.) of the MDP was used to estimate the uniformity of \( \alpha \) particles. Among the slurry-making methods, the NASS method provides the highest uniformity of the slurry microstructure when evaluating the particle size, the MDP, the form factor, and the particle density. To make fine and uniform globular microstructures of the semi-solid slurry in rheocasting, two important factors must be taken into consideration: (i) enhancing the heterogeneous nucleation and (ii) providing uniform growth to increase the form factor of \( \alpha \) particles. Consequently, in considering the above-mentioned factors, the NASS method consisting of a specially designed funnel and artificial agitation using EMS can be used to make high-quality slurry using ADC10 alloy.

### 3.2. Effect of Pouring Temperature on Microstructural Characteristics

As described in Fig. 4, it is also to be noted that the pouring temperature of the melt plays an important role in the evolution of slurry microstructures. Figure 7 shows the ef-

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**Table 3. Quantitative analysis of the slurry microstructures.**

<table>
<thead>
<tr>
<th>Method</th>
<th>Size (( \mu \text{m} ))</th>
<th>Mean Distance of Particles</th>
<th>Form factor</th>
<th>Density (counts/mm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>101 ( \pm ) 10</td>
<td>118.4</td>
<td>0.5</td>
<td>0.7 ( \times ) 10(^3)</td>
</tr>
<tr>
<td>B</td>
<td>75 ( \pm ) 6</td>
<td>125.9</td>
<td>0.7</td>
<td>0.8 ( \times ) 10(^3)</td>
</tr>
<tr>
<td>C</td>
<td>64 ( \pm ) 3</td>
<td>54.8</td>
<td>0.8</td>
<td>1.8 ( \times ) 10(^2)</td>
</tr>
<tr>
<td>D</td>
<td>39 ( \pm ) 2</td>
<td>37.4</td>
<td>0.9</td>
<td>3.8 ( \times ) 10(^1)</td>
</tr>
</tbody>
</table>

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fect of pouring temperature on the microstructure of the slurry made by the NASS method. As shown in the figure, the uniformity and globularity of α particles decrease with the increase of the pouring temperature. At the pouring temperature of 650°C in Fig. 7(a), some coarse rosette-like α particles are found in the slurry, assumed to be caused by the relatively small density of α particles. When the pouring temperature is decreased to 630°C, the morphology of α particles becomes more globular and uniform than it is at 650°C, but some fine dendrites still appeared around the globular α particles. The number of α particles is closely related to the amount of recrystallization via the initial solidification, which can be evaluated from the result of the cooling curves and the particle density. At the pouring temperature of 610°C, the initial solidification started quickly in the melt on the inner surface of the slurry vessel, which led to the decrease in the particle density despite the high ΔT_{sur} value.

The size and distribution of α particles analyzed quantitatively on the microstructures of Fig. 7 are indicated in Table 4. When the pouring temperature was 620°C, uniform α particles with the average size of 39 ± 2 μm were obtained. As the pouring temperature increased, the globular α particles were changed into the coarsened α particles, and the particle density was the highest value in the pouring temperature of 620°C. It is to be noted that fine dendrites were found around the globular α particles above the pouring temperature of 630°C, and dramatically increased at the pouring temperature of 650°C. It is considered that even if the nucleation arose from the vessel wall through the same mechanism, some of the nucleated particles under the high pouring temperature would have selectively survived as coarsened particles. In contrast, the others would have remelted and agglomerated and finally would have remained as fine dendrites.

Fig. 8 shows the magnified microstructures of the slurry obtained using the NASS method for two different pouring temperatures: (a) 650°C and (b) 620°C. In the case of the slurry shown in (a), coarse α particles and fine dendrites are found, and this may cause some problems in feeding the semi-solid slurry into the die cavity in the diecasting process. In addition, liquid (of eutectic composition) segregation in the slurry may lead to the deterioration of the mechanical properties of the final rheo-diecast products. It was found that high-quality semi-solid slurry with fine and uniform microstructures for ADC10 alloy could be obtained with a proper pouring temperature of 620°C, as shown in Fig. 8(b).

<table>
<thead>
<tr>
<th>Pouring temperature (°C)</th>
<th>Globular α particles</th>
<th>Density of fine dendrites (counts/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>Dendritic microstructure with some rosette-like particles</td>
<td>305</td>
</tr>
<tr>
<td>630</td>
<td>217</td>
<td>51 ± 4</td>
</tr>
<tr>
<td>620</td>
<td>404</td>
<td>39 ± 2</td>
</tr>
<tr>
<td>610</td>
<td>228</td>
<td>36 ± 4</td>
</tr>
</tbody>
</table>

*Fine dendrite represents the dendritic particles under the size of 15 μm, as shown in Fig. 8(a)*
3.3. Effect of Heat Treatment Conditions on Hardness

There have been few reports on heat treatment for diecasting products of Al-alloys, such as ADC10 alloy, even though those alloys contained various components, such as Cu, Si, and Mg, related to aging-hardening. Recently, it has been discovered that fine-microstructure aluminum parts indicate high mechanical properties using T6 with a short-time solution treatment.\(^{13,22}\) This is due to the short diffusion length through the grain boundary between the primary \(\alpha\) phase and the eutectic Si particles. Conventional die-casting components cannot be heat-treated at the T6 condition, however, due to internal defects such as blow holes or micro-porosities, despite the short solution time.\(^{23}\) In the case of rheocasting, such casting defects can be prevented using high-quality slurry even for ADC10 alloy, as shown in Fig. 7(c). In the present study, the heat treatment condition was optimized via the constitutional analysis using EMPA and the measurement of the hardness. Figure 9 shows the scanning electron microscope (SEM) images of the microstructures with various \(\alpha\) particles and their constitutional distribution from the electron probe microanalysis (EPMA). The test specimen for the conventional diecasting showed some micro-porosities, as shown in Fig. 9(a). These micro-porosities are known to be expended approximately more than 1 000 times in volume during heat treatment, which leads to some problems such as blister defects and deformation in dimensions. No micro-porosities were detected in the slurry by the NASS method with the pouring temperatures of 650°C and 620°C, as shown in

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Fig. 8. Detailed analyses on the microstructures in the slurry by method-D: (a) non-uniform microstructure consisting of fine dendrites, coarse \(\alpha\) particles, and liquid segregation \((T_{\text{pour}}=630^\circ\text{C})\) and (b) microstructure with fine and uniform globular \(\alpha\) particles \((T_{\text{pour}}=620^\circ\text{C})\).

Fig. 9. The results of the EPMA analysis on the specimens; (a) dendritic microstructure by HPDC \((T_{\text{pour}}=680^\circ\text{C})\), (b) non-uniform and coarse microstructure by method-D \((T_{\text{pour}}=650^\circ\text{C})\), and (c) fine and uniform microstructure by method-D \((T_{\text{pour}}=620^\circ\text{C})\).
However, each of the constitutional distribution showed remarkable differences. Segregation of Si was more significant in the specimen of Fig. 9(b) than that of Fig. 9(c). In Fig. 9(b), the regions with high Si content can be observed between the fine dendrites. The precipitation strengthening of Mg$_2$Si is usually important in artificial aging treatment. Therefore, the severe segregation of Si can be an obstacle to the improvement of the mechanical properties, since it restricts the diffusion of the solute and reduces the efficiency of its normalization in the solution treatment.

The automobile components using ADC10 alloy are...
mainly the high-pressure inner parts and the safety-critical gear case, in which the improvement of strength is required rather than that of elongation. The improvement in strength of the rheo-diecast products can be achieved by heat treatment. The solid solution treatment temperature of Al-alloys is usually 490–540°C, but in cases of alloys with a large amount of the eutectic phase, low solid-solution treatment temperature may be used to avoid partial melting or plastic deformation during heating. To optimize the heat treatment conditions, a hardness test was carried out on the rheo-diecast products of ADC10 alloy. Figure 10 shows the hardness values obtained under the various heat treatment conditions, which were carried out on the rheo-diecast products using the four kinds of slurries, shown in Figs. 5(b) through 5(e). Figure 10(a) indicates the effect of the solid-solution treatment time on the hardness. The solid-solution treatment was carried out at 490°C with various treatment times under the artificial aging at 180°C for 7 h. As the solid-solution treatment time increases, the hardness value increases. As expected from Fig. 6, the rheo-diecast by the NASS method shows the highest hardness value. Figures 10(b) indicate the effect of aging time on the hardness for two different aging temperatures, 180°C and 230°C, respectively. With the aging temperature of 230°C, over-aging occurred within 4–5 h as shown in Fig. 10(b), which is usually applied as the T7 heat treatment. The maximum hardness was achieved when aging at 180°C for 7 h, as shown in Fig. 10(b). The morphology of eutectic Si is known to play an important role in determining the tensile properties of the final casting products. Figure 11 indicates the effect of heat treatment on the eutectic Si morphology. The microstructures in the figure were taken from the heat-treated specimens by the NASS method in Fig. 10(a). As the solution treatment time increases, the eutectic Si changes from coarse plate-like to fine nodular morphology, which may improve mechanical properties, as indicated in Fig. 10(a).

4. Conclusion

In the present study, a new slurry-making method, called the nucleation-accelerated semi-solid slurry (NASS) method, was developed to fabricate high-quality semi-solid slurry of ADC10 alloy for its application to rheo-diecasting. The main results are summarized as follows:

(1) A new slurry-making system consisting of a swirly-shaped funnel and the EMS stirring unit was developed to fabricate semi-solid slurries of the alloys with narrow mushy zones. Through this method, high-quality slurry of ADC10 alloy was successfully obtained and applied to rheo-diecasting.

(2) The pouring temperature of the melt into the slurry-making vessel was found to be closely related to the quality of the semi-solid slurry. The optimum slurry for rheo-diecasting of ADC10 alloy was obtained at the pouring temperature of 620°C. When the pouring temperature was high, i.e., 650°C, coarse and rosette-like α particles were included in the slurry, which could not be properly used for rheo-diecasting. When the pouring temperature was low, i.e., 610°C, the slurry quality deteriorated owing to the initial solidification on the slurry-making vessel surface.

(3) It was found that solute distribution was closely related to the morphology of α particles. In the case of fine and uniform globular microstructure, uniform distributions of Si and Cu were found around the globular α particles. However, in the cases of the microstructures with dendritic or with coarse and rosette-like α particles, the distributions of Si and Cu were not uniform.

(4) The optimized heat treatment condition for the rheo-diecast product of ADC10 alloy was achieved at the solution temperature of 490°C for 30–60 min, water quenching, and age hardening at 180°C for 7–8 h. The highest hardness value was obtained when the slurry had a fine and uniform globular microstructure with uniform solute distributions.

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