1. Introduction

The demands of high energy efficiency and low exhaust emission in automotive industries have elicited much interest in lightweight vehicles. In this context, engine blocks are especially attractive components. They are made of heavy cast iron, but if replaced with aluminum alloys, they can be produced at half their present weight. Gasoline engine blocks are being successfully manufactured via high-pressure die casting (HPDC) processing of ADC10 (AlSi9Cu3) alloy, which is a major alloy used in aluminum engine blocks via HPDC since it has a good castability owing to its narrow solidification range. With diesel engine blocks, however, there are some barriers to the application of HPDC processing in their production. First, much higher mechanical properties are required to bear up against high engine power. Second, inner defects (e.g., gas porosities and shrinkages) should be eliminated for heat treatment. Finally, the high pouring temperature may result in gas entrapment due to the turbulent filling pattern. In order to solve these problems, rheocasting can instead be used in the production of engine blocks. It is an ideal alternative processing method since semisolid slurry achieves lower gas content and laminar flow. In addition, its integral microstructures are heat-treatable, leading to an improvement of mechanical properties.

A new rheocasting process was applied to develop a diesel engine block using ADC10 alloy. This type of diesel engine block requires much higher mechanical properties for a high engine power, and this is why heat treatment for improving mechanical properties should accompany processing. Therefore, the manufacturing process for a diesel engine block must prevent inner defects such as blow-holes, gas porosities and shrinkages. Rheocasting is considered as a manufacturing technique for this purpose. In order to apply the rheocasting technique in manufacturing a diesel engine block, it is important to produce large-volume slurry. Establishing the injection condition has been particularly focused on for the integral inner parts. The Advanced Rheocasting Technology (ART) system, in this study, was used for large-volume slurry with ADC10 alloy. Through computer simulation, the injection condition was determined to stabilize feeding patterns which were verified from experimental results. Various heat treatments were tested to determine the optimal condition for the rheocast diesel engine block. The rheocast engine block showed fine and uniform microstructures, where the average diameter of primary α-globules was 75 μm and its form-factor indicating the degree of globularity was 0.83 including gas contents below 4cc/100 g Al. Mechanical properties indicated 317 MPa Ultimate Tensile Strength (UTS) and 1.2% elongation good enough for the objective usage after modified T6 heat treatment.

KEY WORDS: rheocasting; diesel engine block; ART (advanced rheocasting technology); ADC10 slurry; heat treatment.
incurred substantial costs on the development. Eventually, results of such efforts were not commercialized. Thus, it is necessary to investigate an improved method for large-volume slurry.

Some researchers proposed the selection criteria for the alloy design by computational thermodynamics. These are temperature sensitivity of solid fraction \(\left(\frac{df_{S}}{dT}<0.015\right)\) and solidification range \((10°C<T<150°C)\), which are useful as the alloy selection principles. Considering the criteria for alloy design, however, ADC10 alloy does not seem suitable for making the desirable slurry. Figure 1 exhibits the solid fraction/temperature relationship for AC4C alloy and ADC10 alloy calculated by Thermo-calc. The details of the equilibrium calculations are shown in Table 1. It is noted that the mushy region of ADC10 alloy, \(\Delta T_{L,S}\), is as narrow as 29°C and the solid fraction of \(\alpha\) phase at eutectic temperature is reached at approximately 35%. The temperature sensitivity of solid fraction of ADC10 alloy is relatively high at 0.015% K\(^{-1}\). These criteria based on thixocasting may not be completely applied to rheocasting. Since in thixocasting, reheated billet should be handled by a robot, it cannot be applied at a low solid fraction. On the other hand, a slurry with both a high and low solid fraction is available in rheocasting. If there are various nucleation sites well dispersed through the whole parts of the slurry, it might be possible to produce slurry even in ADC10 alloy despite a narrow solidification range.

In this study, a new method called Advanced Rheocasting Technology (ART) developed by Hong and NanoCastKorea for the production of large-volume slurry for ADC10 alloy was suggested. In the method, the molten metal is poured into a specially designed vessel, applying electromagnetic stirring (EMS) to generate small and copious \(\alpha\) particles in the inner vessel as a wall nucleation effect at the early stage of solidification. During the cooling stage in the slurry-making vessel, uniform distribution of temperature and solute in the slurry maintained by EMS can effectively contribute to the growth of \(\alpha\)-particle in the shape of globules.

This work aimed at developing a rheocast diesel engine block with ADC10 alloy, using the ART system. An injection system for the stable feeding behavior of the slurry was established. To obtain the required mechanical properties of the diesel engine block, heat treatment conditions were optimized.

2. Experimental Procedures

2.1. Preparation of a Rheocast Engine Block Using the ART System

The commercial ADC10 alloy, which is a general material for manufacturing an engine cylinder block for high pressure diecasting (HPDC), was used in this study. The chemical composition of this alloy is shown in Table 2. The molten liquid of ADC10 alloy was held at 640±5°C after degassing using pure argon gas with the degassing chemical tablet (N\(_2\)) injected into the melt at 700°C. Figure 2 shows the schematic drawing of the ART slurry maker and the specially designed vessel. The ART slurry maker was composed of three kinds of EMS equipment with power controlled by equivalent Ampere (10–30 A). With this condition, the electromagnetic field of 200–600 G was led for aluminum molten metal of 25 kg in the slurry making vessel (φ180 mm in diameter, 500 mm in length). To make the slurry, the melt was poured into the vessel at 610°C and was taken out of the vessel at 590°C. The solid fraction at this temperature is of about 0.15, which is the equivalent temperature obtained by Thermo-Calc.

Figure 3 shows the schematic drawing of the ART system integrated with HPDC machine for casting diesel engine blocks. The engine blocks were manufactured by a 3 500-ton Buhler diecasting machine. Each slurry weighing approximately 25 kg was lifted to the sleeve from the slurry maker by an automatically controlled robot. Compared to other rheocasting processes, the ART system occupies a small working area due to its simpler layout so it is not necessary to change existing facilities except setting the robot transferring the slurry.

The engine block produced in this study is the flat-four-open deck type cylinder block with a cast iron liner combined into the bore mechanically using the rough surface with protrusions of the liner during casting. In HPDC processing by molten liquid at 650–670°C, the temperature of the liner was held at about 250°C before insertion into each bore to avoid solidification problem during feeding. This joining type can cause some solidification problems in rheocasting because slurry is injected at a lower temperature compared to HPDC processing. Therefore, the joining
conditions between the liner and the slurry were investigated.

In the mold system of the engine block, the total gate area was enlarged approximately 1.7 times compared to HPDC processing to induce the laminar feeding pattern. The mold temperature was maintained from 220 to 250°C using the mold heating system. The sleeve temperature was set at approximately 200°C to prevent the formation of solidification shell in the sleeve prior to injection.

The computer simulation was carried out in order to analyze the following: (i) the velocity for laminar feeding at the ingate; (ii) prediction of the feeding behavior; and (iii) shrinkage formation. In order to calculate the feeding characteristics of the slurry, Anycasting software was used with the semi-solid module. The casting parameters and computation conditions used for the simulation are summarized in Table 3. The proper injection condition was suggested by calculating the Reynolds number at the ingate during filling in the cavity. The effects of several injection conditions on the feeding characteristics were simulated by Anycasting software and compared with the experimental results.

2.2. Analysis of the Rheocast Engine Block

Analysis of the computerized tomography (CT) image scan on the engine blocks produced was carried out to examine the interior problems of the defects caused by unstable feeding and shrinkage. To investigate the effect of micro-porosities on blistering or any surface defects after heat treatment, the amount of the micro-porosities in the specimens was analyzed by measuring bulk density via Archimedes method.

For the microstructural observation, all samples were ground by SiC papers and polished on a cloth with 0.04 μm diamond suspension. The microstructures were analyzed using a microscope fitted with a digital camera and an image analyzer software. The specimens for tensile tests were taken from the crank journal parts of the engine blocks produced. This was machined to a plate type with a thickness of 2 mm and a gauge length of 20 mm. Tensile test was performed on a hydraulic ‘Instron 8500 system’ connected to a PC for automated testing along with the calculation of mechanical properties.

3. Results and Discussion

3.1. Large-volume Slurry Making with ADC10 Alloy via ART

Generally, in case of small volume-slurry under φ80 mm in diameter, the desired globular microstructure is obtained by the control of pouring temperature and cooling rate without any mechanical agitation. However, as the volume of slurry increases, it becomes difficult to uniformly control temperature distribution in the slurry making vessel. Figure 4 shows a schematic drawing of the newly developed slurry maker designed to solve problems attributed to the larger volume. The optimal conditions for making large-volume slurry of 25 kg have been determined numerically and experimentally. In particular, the fluid velocity caused by EMS which influences heat and mass transfer should be controlled very carefully for ADC10 slurry due to a relatively small amount of α phase compared to that of AC4C prior to eutectic solidification. For numerical calculation, we used the Navier–Stokes Equation with the Lorentz force term as follows:

\[
\rho \frac{dv}{dt} = \rho g - \Delta p + \eta \nabla^2 V_t + F_L \quad \text{(1)}
\]

Considering steady state, \(\rho g\) and \(\Delta p\) are zero in Eq. (1).
Where Lorentz force $F_L$ is defined as Eq. (2)

$$F_L = f(r,z) \frac{1}{2 \rho} \omega \sigma |B|^2 \frac{H}{R} < \infty \quad \text{.........(2)}$$

where $f(r,z)$ is a compensation function related to the cylinder volume radius $r$ and height $z$.

Consequently, the fluid velocity $V_\theta$ by EMS can be expressed as Eq. (3).

$$V_\theta = \frac{\omega \sigma B r^2}{16 \eta p} \left[ -r^3 + r (r_1^2 + r_2^2) - \frac{r_1^2 r_2^2}{r} \right] \quad \text{.........(3)}$$

where $\rho$ is the pole pair of yoke, $\omega$ the angular frequency of magnetic field, $B$ the radial magnetic flux density, $\eta$ the fluid viscosity, $r_1$ and $r_2$ are inner and outer radii of the annular flow field respectively.

From the various experiment results, when the magnetic flux density was 600 Gauss in radial direction, fluid velocity of 280 rpm was obtained at the outer region on the conditions with the voltage of 240 V and the frequency of 60 Hz. The microstructure of slurry was uniform with distributed $\alpha$-Al globules of 75 $\mu$m in average diameter in those EMS condition. In order to have uniform stirring forces in the molten aluminum during slurry making, the EMS equipment should consist of three parts of stirring units, as shown in Fig. 4.

**Fig. 4.** Comparison with the slurry-making method; (a) liquidus casting method\textsuperscript{26} and (b) ART (Advanced Rheocasting Technology).

Table 3. Casting parameters and computation conditions used for the simulation.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Unit</th>
<th>Values</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solidus temperature</td>
<td>$T_s$</td>
<td>°C</td>
<td>568</td>
<td>Fixed</td>
</tr>
<tr>
<td>Liquidus temperature</td>
<td>$T_l$</td>
<td>°C</td>
<td>597</td>
<td>Fixed</td>
</tr>
<tr>
<td>Latent heat</td>
<td>$Q$</td>
<td>kJ/kg</td>
<td>389</td>
<td>Fixed</td>
</tr>
<tr>
<td>Initial SSM temperature</td>
<td>$T_0$</td>
<td>°C</td>
<td>590</td>
<td>Fixed</td>
</tr>
<tr>
<td>Initial die temperature</td>
<td>$T_d$</td>
<td>°C</td>
<td>220–250</td>
<td>Fixed</td>
</tr>
<tr>
<td>Initial sleeve temperature</td>
<td>$T_s$</td>
<td>°C</td>
<td>200</td>
<td>Fixed</td>
</tr>
<tr>
<td>Heat transfer coefficient between material and</td>
<td>$h_m$</td>
<td>W/m²K</td>
<td></td>
<td>Value depends on</td>
</tr>
<tr>
<td>mold</td>
<td></td>
<td></td>
<td></td>
<td>die position</td>
</tr>
<tr>
<td>Apparent viscosity of molten liquid</td>
<td>$\eta$</td>
<td>Pa s</td>
<td>$\sim$0.010</td>
<td>Value depends on</td>
</tr>
<tr>
<td>Apparent viscosity of the ADC10 SSM slurry</td>
<td>$\eta$</td>
<td>Pa s</td>
<td>0.5–0.9</td>
<td>Value depends on</td>
</tr>
</tbody>
</table>

**Fig. 5** shows the representative microstructures of the slurry obtained by the ART system, compared to the liquidus casting method.\textsuperscript{28} The melts were poured into the slurry making vessel at the temperature of 610°C and the slurry was quenched into the water at 590°C. The microstructure, without any agitation, shows coarsened dendritic $\alpha$ phase. With the ART system, the microstructure consisting of $\alpha$-globules was obtained, known to be available as semisolid slurry,\textsuperscript{2} as shown in Fig. 5(b). Through turbulent mixing of the melt by the ART system, the melt has a uniform field of temperature and solute during nucleation, leading to an increase in heterogeneous nucleation sites at the early stage of solidification.\textsuperscript{21} Furthermore, during the cooling stage in the slurry making vessel, uniform distribution of temperature and solute in the melt prevent the formation of dendritic growth that results in globular microstructures.

### 3.2. Establishment of an Injection System for the ADC10 Slurry

The injection condition is one of the most important factors that allow an integral product to be obtained, without blow holes, porosities, cold shut, etc. The use of slurry can minimize the aforementioned problems owing to its laminar feeding behavior in low injection speed. There have been many reports of the effect of injection speed on the feeding behavior in rheocasting with AC4C slurry. Figure 6 summarizes the typical injection system in the case of the AC4C slurry.\textsuperscript{22,23} When the AC4C slurry is poured into a long sleeve, the outer region of the slurry easily solidifies in the sleeve because its solid fraction is high (0.4). High-speed initial injection not only helps reduce the contact time in the sleeve but also helps address the solidification problem at the outer region of the AC4C slurry, as shown in the stage $B$ in Fig. 6.\textsuperscript{24} When the slurry passes through the ingate, the ingate speed should be controlled, under which the laminar feeding behavior can be induced along the ingate area, the volume and shape of the product, etc. The C-E stages in Fig. 6 show the examples of injection condition designs for high-quality semisolid products.

The solid fraction of the ADC10 slurry, however, is low (0.2). Therefore, the apparent viscosity of the slurry during feeding in the mold cavity is relatively lower than that of the AC4C slurry due to the lower solid fraction. Thus, it is necessary to modify the typical injection system for laminar feeding for the ADC10 slurry. For example, the injec-
tion speed at the initial stage (B), as shown in Fig. 6, should be kept as low as possible to prevent air entrapment in the sleeve because of the low viscosity of the ADC10 slurry. The injection speed of the ingate should also be determined by taking into account the characteristics of the ADC10 slurry. The characteristics of slurry feeding were estimated through the Reynolds number to determine appropriate injection speeds, using the parameters obtained by Anycasting software. It is generally known that the Reynolds number is the criterion used for distinguishing the flow characteristics of slurry, as in the following equation:

\[ Re = \frac{\rho v D}{\eta} \] .................................(4)

where \( Re \) is the Reynolds number, \( \rho \) the density of the alloy, \( v \) the ingate speed, and \( D \) the diameter of the pipe. Considering the shape of the ingate \( D \) is defined as Eq. (5).

\[ D_e = \frac{2wt}{(w+t)} \] .................................(5)

where \( D_e \) is the equivalent diameter, \( w \) the width, and \( t \) the thickness.

Generally, the condition of the Reynolds number defines the flow characteristics in a pipe, as in the following conditions: \( Re < 2100 \): laminar flow; \( 2100 < Re < 4100 \): transient flow; \( Re > 4100 \): turbulent flow.

The calculation parameters as well as the results of the Reynolds numbers of the various injection speeds are shown in Table 4. In HPDC processing using molten liquid, the flow pattern was verified as a turbulent flow despite the low injection speed. The ADC10 slurry, however, showed a Reynolds number that was low enough to induce laminar feeding at a low injection speed, even if the ADC10 slurry had a low solid fraction. When the injection speed was increased, the Reynolds number also increased. It was predicted that the feeding behavior of the ADC10 slurry would be converted by turbulent flow over the injection speed of 1.0 m/s.

The range of the injection speed for laminar feeding was identified as a low Reynolds number on the low-injection-speed condition, but the long filling period due to low injection speed may cause the formation of solidification shell during feeding in the mold cavity. In order to avoid this problem, the injection system of the ADC10 slurry was set up as shown in Fig. 7. Considering the characteristics of the ADC10 slurry, the injection speed was maintained at 0.25 m/s at the initial stage and then, in the mold cavity increased to 0.5 and 1.0 m/s, corresponding to the limited velocity for the laminar flow. When the slurry passes through the ingate into the mold cavity, the injection speed set above 0.5 m/s because of the long filling time.

The investigation of the effects of rheocasting on the quality of a diesel engine block was carried out using the aforementioned injection systems. The rheocast engine block was compared with the conventional HPDC engine block.

### 3.3. Effect of the Rheocasting Process on the Quality of the Engine Blocks

The filling sequences in both HPDC processing and rheocasting were simulated using Anycasting software as shown in Fig. 8. Unstable feeding patterns are obvious in all the filling sequences in HPDC processing, as can be seen in Fig. 8(a). However, the feeding patterns in rheocasting are changed dramatically into stable feeding patterns. The typical laminar filling sequence, in particular, was predicted under the 0.5 m/s injection velocity condition, as shown in Fig. 8(c). When the injection velocity was 1.0 m/s, the local unstable feeding pattern (Fig. 8(b)) was observed in the head-face of bore due to the narrow thickness.

Figure 9 shows the simulation results on the final solidified region and the velocities of the feedstock at the same
filling sequence, compared with the results of the analysis of the CT image. In the HPDC engine block, the CT image scan in Fig. 9(a) showed shrinkage porosity and local filling defects. These defects are similar to the typical defects in some complicated HPDC products. Considering the simulation results in Fig. 9(a), it seems that shrinkage porosity was caused by the isolation of the high-temperature region. Since the pouring temperature in HPDC processing is usually as high as 650–660°C, the high-temperature region can be easily isolated in the thick parts. The fast injection speed in HPDC processing also caused the turbulent flow patterns, leading to filling defects such as air entrapment or blow holes in the inner part, as shown in the arrows of the CT image scan in Fig. 9(a). In the rheocast engine blocks, however, the defects in HPDC processing decreased by stable feeding, using the slurry that was injected at the low feeding temperature of 590°C, as shown in Fig. 9(b) and 9(c). The shrinkage defects as well as porosities observed in the HPDC engine block were not detected in the rheocast engine block at the injection speed of 0.5 m/s. Prevention of these defects via rheocasting enabled the diesel engine block to be heat-treatable. These defects might cause the formation of blister or distortion in the casting during the heat treatment.

Another essential analysis of the heat-treatable conditions was required in the bore parts combined with the cast iron liner. Figs. 10(a) and 10(b) show the optical photographs while Fig. 10(c) shows the microstructures of the bore parts in the rheocast engine block. These parts, which are mechanically combined by different materials, are expected to become weak points during heat treatment if they have some defects in the joining zone. The joining ratio, which is defined as the ratio of the soundly combined region to the total bore surface, is usually used for estimating the joining state. However, no problems were assured because the joining ratio over the average of 99.5% was obtained in all the bore parts on the rheocast engine block, as shown in Fig. 11. The joining ratio of the rheocast engine block was higher than that of the HPDC engine block (Ave. 95%). This result demonstrated that the joining condition was affected by the feeding characteristics in this study rather than by the temperature of the feedstock.

### 3.4. Analysis of the Microstructures of the Rheocast Engine Block

It is generally known that some defects, such as segregation and the presence of microporosities, should not exist in the interior of the products for the heat treatment. Moreover, the inherent gas quantity should be as low as possible because these defects and gases cause blistering on the sur-
face or reduce the mechanical properties of the engine block due to the expansion that occurs during the heat treatment.

The representative microstructures obtained by the rheocast and HPDC engine blocks are presented in Figs. 12(a) and 12(b), respectively. The microstructure of the rheocast engine block had a fine and globular $\alpha$ phase, as shown in Fig. 12(a). In the HPDC engine block, however, a very fine dendritic microstructure and some microporosities were observed, as shown in Fig. 12(b). This was attributed to the scattering of the molten liquid by the high injection speed in HPDC processing. The microporosities do not affect the performance of non-heat-treatable engine blocks (e.g., the gasoline engine) but should be diminished for the diesel engine block because high mechanical properties are required by heat-treatment.

To examine microstructural uniformity in the rheocast
engine block, various positions were analyzed. Figure 13 shows a photograph of the final product and the microstructures observed at the initial injected part, the bore parts, and the final feeding part in the rheocast engine block. For the analysis of the slurry’s microstructural quality, quantitative microstructural parameters such as particle size and form factor were used, where form factor \( (F) \) is the index for the globularity of \( \alpha \) phase. It was calculated using the following equations:

\[
D_e = \sqrt[3]{\frac{4A}{\pi}} \quad \text{and} \quad F = \frac{p^2}{4\pi A},
\]

where \( D_e \) is the equivalent diameter of the particle, and \( A \) and \( p \) are the area and perimeter of the particle, respectively.

Quantitative analysis of the microstructure of each part in Fig. 13 is presented in Fig. 14. It is well known that segregation of the microstructures poses a problem in the reduction of the mechanical properties, which often occurs in HPDC processing. On the other hand, the rheocast engine block showed uniform microstructures in all parts. The size of \( \alpha \) phase averaged 75 \( \mu \text{m} \), and its form factor averaged 0.83. As shown in Fig. 13, the microstructures including \( \alpha \)-globules are relatively uniform so that the slurry produced by the ART slurry maker is suitable for maintaining a stable feeding pattern without liquid segregation through the injection system. Moreover, comparison of the gas contents showed that the rheocast engine block has more integral characteristics compared with the HPDC engine block. Figure 15 shows the gas contents of the rheocast engine block in each position in Fig. 13, compared with those of the HPDC engine block. An average 80% reduction of the amount of gas was accomplished in rheocasting. The rheocast engine block had less than 4 cc gas per 100 g Al in all positions.
its parts, which was low enough to be heat treatment. These results are attributed to the low gas solubility of the rheocast engine block owing to the low pouring temperature and stable feeding behavior produced by the laminar flow.

3.5. Determination of the Optimal Heat Treatment Conditions for the Rheocast Engine Block

It has been recently discovered that fine-microstructure aluminum components indicate high mechanical properties using T6 with a short-time solution treatment. This is because of the short diffusion length through the grain boundary between the primary phase and the eutectic Si particles. However, conventional die-casting components cannot be heat-treated at the T6 condition due to internal defects such as gas and shrinkage porosities, in spite of the short solution time. On the other hand, in the case of the rheocast engine block produced by the ART process, heat-treatable values of few porosities and a gas content of 4 cc/100 g Al were obtained, as shown in Figs. 12 and 15. The results of the surface blister and dimensional instability tests (solution treatment at 520°C/7 h) are shown in Fig. 16.

In the case of the HPDC engine block, the high pressure due to the gas expansion inside the pores revealed surface bubbles and caused plastic deformation (Fig. 16(a)), as pointed by arrows, while the use of the rheocast engine block resulted in a clean surface without blister defects (Fig. 16(b)).

For the diesel engine block, over 300 MPa Ultimate Tensile Strength (UTS) and over 1% elongation are required to achieve adequate performance. Accordingly, to determine the solution heat treatment temperature and time for the diesel engine block made of ADC10 alloy, various solution heat treatment conditions were applied. Table 5 presents the mechanical properties and soundness that were acquired for various heat treatment conditions. The heat-treatment consisting of solution treatment and artificial aging was carried out to improve mechanical properties such as UTS and yield strength. The effect of solution treatment conditions, such as treatment temperature and time, were examined on mechanical properties, as shown in Table 5. The T5 temper was used only for comparison purposes because it is often used for dimension stability in HPDC processing. The UTS over 300 MPa and the elongation over 1% are achieved by T6 treatment. In terms of reliability (the rate of the sound specimen), however, only the rheocast engine blocks expressed high reliability after the heat treatment. Consequently, the optimal T6 treatment was determined to be ideal for a solution heat treatment at 490°C/0.5 h, water quenching, and age hardening at 170°C/9 h. Figure 17

Table 5. Mechanical properties of two processing methods obtained by various heat treatment conditions.

<table>
<thead>
<tr>
<th>Methods</th>
<th>Heat treatment conditions</th>
<th>Yield Strength (YS) (MPa)</th>
<th>Ultimate Tensile Strength (UTS) (MPa)</th>
<th>Elongation (%)</th>
<th>Reliability (sound specimens/total specimens)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPDC Processing</td>
<td>F As-cast</td>
<td>162.1</td>
<td>224</td>
<td>0.8</td>
<td>9/10</td>
</tr>
<tr>
<td></td>
<td>T6_1 Solution (520°C/7h); Aging (170°C/7h)</td>
<td>209.8</td>
<td>295.3</td>
<td>2.1</td>
<td>1/10</td>
</tr>
<tr>
<td></td>
<td>F As-cast</td>
<td>188.2</td>
<td>213.2</td>
<td>2.1</td>
<td>10/10</td>
</tr>
<tr>
<td></td>
<td>T6_1 Solution (520°C/7h); Aging (170°C/7h)</td>
<td>212.2</td>
<td>325.4</td>
<td>0.8</td>
<td>8/10</td>
</tr>
<tr>
<td>Rheocasting</td>
<td>T6_2 Solution (520°C/7h); Aging (170°C/9h)</td>
<td>215.2</td>
<td>312.8</td>
<td>1.1</td>
<td>9/10</td>
</tr>
<tr>
<td></td>
<td>T6_modified Solution (490°C/0.5h); Aging (170°C/9h)</td>
<td>229.5</td>
<td>317.6</td>
<td>1.2</td>
<td>10/10</td>
</tr>
<tr>
<td></td>
<td>T5 Aging(170°C/7h)</td>
<td>192.2</td>
<td>247.2</td>
<td>1.3</td>
<td>10/10</td>
</tr>
</tbody>
</table>

Fig. 16. Optical pictures and microstructures of the crank journal part obtained by (a) the HPDC engine block and (b) the rheocast engine block, after the solution treatment at 520°C/7 h.

Fig. 17. Microstructures of the rheocast engine block after various heat treatments: (a) F condition, (b) T5 condition, (c) T6_1 condition, and (d) T6_modified condition.
shows the microstructures in the conditions presented in Table 5. The fine and nodular eutectic phase was detected in both the T6 and T6_modified treated specimens. Comparing the eutectic Si, however, the morphology of T6_modified is finer and more fibrous than that of T6, as shown in Fig. 17(c). This means that coalesced eutectic silicon debases the strength and ductility of engine blocks due to the high stress intensity in the eutectic regions.

4. Conclusion

A heat-treatable diesel engine block made of ADC10 alloy was developed in this study by means of rheocasting, produced by the ART slurry maker. The following conclusions were obtained:

1) A large-volume (25 kg) slurry of ADC10 alloy was produced using the ART system. The slurry was produced despite the narrow solidification range and high sensitivity of solid fraction in the ADC10 alloy, through the nucleation effect of the ART system.

2) The injection condition for the ADC10 slurry was set up through the computer simulated analysis and the stable feeding patterns were verified from experimental results. When the slurry was injected by 0.5 m/s in the ingate, the integral rheocast engine block was obtained.

3) The rheocast engine block showed fine and uniform microstructures at all positions, where the size of the α particles averaged 75 μm and the form factor averaged 0.83. Analysis of the gas amount demonstrated that the rheocast engine block is suitable for heat treatment.

4) The optimized conditions for the diesel engine block were obtained from the various heat treatment conditions that were used in this study. The optimized solution treatment conditions are heat treatment at 490°C/0.5 h, water quenching, and age hardening of 170°C/9 h. Rheocasting reduced the microporosities, filling defects, blow holes, and shrinkage defects that abound in HPDC processing. Consequently, the rheocast engine block satisfied the required mechanical properties for a high reliable diesel engine.

Acknowledgments

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