Improvement of Microstructure in Hypereutectic Al–Si Alloys by Rheocasting

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An investigation was made on the viscous flow and microstructure in hypereutectic Al–Si alloys rheocast with the rotation of a stirrer at a high speed in the range from 30 to 70 rev/s. The value of apparent viscosity in Al–Si alloys solidifying with the rotation of stirrer at a speed above 30 rev/s remained almost unchanged to a certain level except a rapid change at the initial stage of solidification. The average size of primary silicon was 66 ± 19 μm in an Al–21.5%Si–3.5%Cu–0.3%Fe–0.1%Mg alloy ingot rheocast at 70 rev/s under the cooling condition at a rate of 0.6 K/s in the melt. The primary silicon size became finer by the modification of microstructure with an addition of 0.01% Na or 0.01 and 0.1% P in rheocast and conventionally cast hypereutectic Al–Si alloys. A constant level of apparent viscosity was also observed during the high-speed rheocasting of an Al–15.4%Si–4%Cu–1.1%Ni–1%Fe–0.3%Mn–0.2%Ti–0.1%Mg–0.02%Zn–0.01%Na alloy ingot. It was depressed with the increase in rotation speed of a stirrer from 30 to 50 rev/s. The primary silicon size of the alloy ingot was 101 ± 27 μm at a rotation speed of 30 s⁻¹, 96 ± 25 μm at 40 s⁻¹ and 93 ± 25 μm at 50 s⁻¹.

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I. Introduction

Hypereutectic Al–Si alloy castings are well-known to be a material with the most superior antifrictional properties. However, these castings containing inherent casting defects do not have good mechanical properties fit for forging and precise cutting(1).

In order to avoid the casting defects and improve the material characteristics in hypereutectic Al–Si alloys, the rheocasting at high rotation speeds(2)–(7) has been applied to the alloys. In the previous rheocasting at high speeds(2)–(7) grain refinement has been accomplished by fragmentation of dendritic crystals with the rotation of stirrer at high speeds. Unfortunately the morphology of a primary silicon formed inherently by a hypereutectic Al–Si alloy is recognized by microstructural observation not to be a dendrite but to be a polyhedron. Therefore, it is a very important problem for the practical use of hypereutectic Al–Si alloys as an antifrictional material to examine the limit of the refinement of primary silicons by the high-speed rheocasting.

In the present work, the comparison of the microstructures in hypereutectic Al–Si alloys rheocast at high rotation speeds with those in the conventionally cast alloys, the variation in torque during the solidification of these alloys, the evaluation of apparent viscosity of solidifying alloys based on the value of torque induced by the alloys, the mutual relation between microstructure after solidification and apparent viscosity of solidifying alloys, and the effects of rotation speed of stirrer and grain refiners of Na and Cu–P on the size of primary silicon particles in the hypereutectic Al–Si alloys are investigated.

II. Experimental Procedure

The compositions of the hypereutectic Al–Si alloys which are chemically analysed after the present rheocasting is shown in Table 1. The outline of an experimental apparatus to rotate
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A chamber provided thereof in the front panel of a door for permitting insertion of a graphite crucible into the chamber and inspection of the interior of the chamber constitutes a vacuum container. The interior of the chamber is partitioned into upper cooling and lower heating rooms by a shutter made of molybdenum and adapted to be opened and closed by an air cylinder. Inside the lower heating room is disposed a resistance heating furnace of molybdenum in which a graphite crucible is supported with a molybdenum cup on a support bar so as to be movable up and down automatically. The upper cooling room has a water-cooling outer tube therein, and a graphite stirring bar is suspended downward into the center of water-cooling outer tube. The stirring bar is so constructed that it may be rotated at the superhigh speed up to 75 s⁻¹ by a motor provided at the upper end thereof. The motor is provided on the rotary shaft with a torque detector and a rotation detector connected with a digital unit for displaying and recording both the torque of stirring bar and the rotational speed to be detected simultaneously. A recorder attached to the tip of a Chromel-Alumel thermocouple set at the center of side wall of the crucible in the aforementioned apparatus is also operated to record the changing temperature in a continuous curve.

The experimental procedure is as follows. First of all, a material prepared for the chemical composition of hypereutectic Al-Si

| Alloy | Si   | Cu | Mg | Fe | Ni | Ti | Mo | Cr | Mn | Zn | Al | Na | P  |
|-------|------|----|----|----|----|----|----|----|----|----|----|----|----|
| A     | 17.2 |    |    |    |    |    |    |    |    |    |    |    | Bal.|
| B     | 22.9 |    |    |    |    |    |    |    |    |    |    |    | Bal.|
| C     | 21.5 | 3.5| 0.1| 0.3|    |    |    |    |    |    |    |    |    |
| D     | 21.5 | 3.7| 0.1| 0.3|    |    |    |    |    |    |    |    |    |
| E     | 21.6 | 3.5| 0.1| 0.3|    |    |    |    |    |    |    |    |    |
| F     | 21.5 | 3.6| 0.1| 0.3|    |    |    |    |    |    |    |    |    |
| G     | 21.7 | 3.6| 0.1| 0.3|    |    |    |    |    |    |    |    |    |
| H     | 20.4 | 3.5| 0.1| 0.3|    |    |    |    |    |    |    |    | Bal. 0.01|
| I     | 20.6 | 3.5| 0.1| 0.3|    |    |    |    |    |    |    |    | Bal. 0.01|
| J     | 20.6 | 3.5| 0.1| 0.3|    |    |    |    |    |    |    |    | Bal. 0.1|
| K     | 13.3 | 3.6| 0.1| 0.8| 0.9| 0.2|    |    |    |    |    |    |    |
| L     | 15.4 | 4.0| 0.1| 1.0| 1.1| 0.2|    |    |    |    |    |    |    |
| M     | 19.8 | 3.8| 0.1| 1.1| 1.1| 0.2|    |    |    |    |    |    |    |
|       |      |    |    |    |    |    |    |    |    |    |    |    |    |

A stirrer at a speed above 30 s⁻¹ (1800 rpm) during the solidification of these alloys and to make primary silicon crystals into fine particles is represented in Fig. 1.
system is placed in the crucible and then the chamber is evacuated with a vacuum pump, and the shutter over the heating furnace is closed to heighten the efficiency of heating. When the degree of vacuum attains $1 \times 10^{-3}$ Pa, the material in the crucible is heated to melt into a hypereutectic Al–Si alloy weighing 0.5 kg. After the alloy material in the crucible has been thoroughly melted and kept at 1100 K for a period of 1800 s for the homogenization of the melt, the shutter over the furnace is opened and the support bar supporting the crucible by the bottom thereon is raised by an elevating mechanism until the crucible is located inside the water-cooling outer tube. As a result, the stirring bar is gradually inserted at a rising rate of $2.5 \times 10^{-2}$ m/s into the molten alloy in the crucible until the leading end of the stirring bar reaches a distance of 0.01 m from the bottom wall of the crucible. At this time, the length of the stirring bar immersed in the molten alloy is about 0.1 m.

Then, flow of cold water through the water-cooling outer tube is started to effect cooling of the molten alloy at a rate of 0.6 K/s, while the stirring bar is kept rotated at a low speed of 18 s$^{-1}$ in order to homogenize the composition and temperature of the melt. The rotational speed of the stirring bar is raised in an interval of 10 s to a high speed in four stages of 30, 40, 50 and 70 s$^{-1}$, after the alloy material has substantially reached the temperature for starting solidification in recorded cooling curve and torque. In this case, the rotational speed is increased at a fixed rate so as to prevent the almost molten state alloy from being scattered in consequence of a sharp increase in rotation speed. Subsequently the rotational stirring at the fixed speed indicated above is continued until immediately before the temperature for completion of solidification is confirmed based on the cooling curve of the recorder and the torque value on the digital display device. Then the support bar supporting the crucible is descended by the falling mechanism, until the leading end of the stirring bar reaches a distance of 0.2 m from the bottom wall of the crucible in order to prevent the stirring bar from adhering to the rheocast alloy ingot. As a result, primary silicon crystals inherently formed by the alloy are partly melted and transformed into smaller primary silicon particles by the violent fluid flow with the rotation of stirrer at a high speed during the solidification of hypereutectic Al–Si alloys.

In order to aim at further refinement of primary silicon crystals, the effect of grain refiners of Na$^{(9,10)}$ and Cu–P$^{(10,12)}$ on the size of primary silicon particles in high-speed rheocasting and conventional casting of hypereutectic Al–Si alloys is investigated by addition of 0.01% Na or 0.01 and 0.1% P to Al–Si alloys shown in Table 1.

Furthermore a metallurgical observation is made on the top, middle and bottom sections cut transversely from the rheocast alloy ingot by an optical microscope. The size of primary silicon particles is determined on ten microphotographs of the rheocast alloy by an automatic image analysis system under the condition of residual error of $\sigma = 5\%$.

The stirring bar has generally a square cross section and is tapered 0.030 m at the upper end to 0.025 m at the lower end with the four corners cut off as illustrated in the previous work$^{(6)}$. The graphite crucible is 0.078 m in outer diameter, tapered 0.060 m in inner diameter at the upper end to 0.055 m at the lower end, and 0.130 m in depth. The measurement of torque is made by a digital torquemeter connected with a torque detector, which is attached to a rotary shaft having a stirrer at the lower end of the shaft. The value of torque induced by the viscosity of solidifying alloys is the difference between the torque value recorded on a digital printer and the standard value of torque during the rotation of stirrer in an empty crucible without the semi-solid alloys in the same condition.

**III. Experimental Results and Discussion**

1. **Microstructure in rheocast alloys**

Optical microphotographs in alloys A and B shown in Table 1, i.e. Al–17.2%Si and Al–22.9%Si binary alloy ingots rheocast at a rotation speed of 70 s$^{-1}$ are shown in Fig. 2. The size of primary silicon particles is $89 \pm 30 \mu m$ in alloy A or $96 \pm 34 \mu m$ in alloy B. The primary
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Silicon particle size remains almost unchanged in spite of difference in silicon content between both alloys.

A comparison of high-speed rheocasting with conventional casting is carried out on the basis of microstructural observation for alloy C with multicomponent system. A result of it is represented in Fig. 3. Figure 3(a) shows a microstructure in conventionally cast alloy C. Figure 3(b) shows a microstructure in alloy C rheocast at a rotation speed of 70 s⁻¹. Primary silicon particles are observed in both micro-structures of the alloy ingots produced by the above two casting methods. Then the size of primary silicon particles is calculated by an automatic image analysis system under the condition of residual error of $\sigma = 5\%$. On the assumption that the primary silicon size is represented by $X \pm R$, where $X$ is its average value and $R$ is its standard deviation. The particle size is $236 \pm 49$ or $66 \pm 19 \mu m$ in the alloy ingot conventionally cast or rheocast at 70 s⁻¹. It is concluded that the primary silicon particle size is decreased below one third by the rota-
tional stirring during solidification.

2. Variation in torque during rotational stirring

The variation in torque of hypereutectic Al-Si alloys solidifying under the condition of continuous cooling inside the water-cooling tube is investigated. As a result, the variation of torque in alloy K for Al-13.3%Si, L for Al-15.4%Si or M for Al-19.8%Si is shown in Fig. 4, where the temperature for start of solidification (start of rotational stirring) is 926, 931 or 920 K and the temperature for the end of rotational stirring is 830, 829 or 831 K. The values of torque induced by alloys K, L and M represent an approximately equivalent value of 0.22 N·m in the beginning of solidification, but remain almost unchanged at a level of 0.10, 0.22 and 0.15 N·m in the majority of solidifications. Then the change in torque during the solidification with rotational stirring is explained as follows. In general the value of torque controlling the apparent viscosity of a solidifying alloy is increased with the advance of solidification in a conventional rheocasting at low rotation speed of stirrer speeds below 17 s⁻¹(13). However, in the present rheocasting at high stirrer speeds above 30 s⁻¹ the value of torque remains unchanged as a result of the increase in actual viscosity of the solidifying alloy and the decrease in the osculating plane between the alloy and the stirrer by strong centrifugal force with high-speed rotation of stirrer. In the present experiment the cooling rate from the insertion of stirrer into the vacuum-melted alloy to the start of solidification in the alloy is 0.6 K/s, the same in every alloy, but the cooling rate from the start of solidification to just before the start of crystallization of eutectics is 0.31, 0.46 or 0.39 K/s in alloy K, L or M, respectively. Considering that the sizes of primary silicon particles do not greatly differ from one another, the value of torque in alloys K, L and M should be controlled by the cooling rate from the start of solidification to the beginning of eutectics formation in them.

3. Apparent viscous flow in the solidification with rotational stirring

In order to evaluate quantitatively the viscous behavior of solidifying Al-Si alloys experiencing the rotation of stirrer, the value of apparent viscosity is calculated by the following equation(13)-(15),

\[ \eta = M(1 - \alpha^2)/4\pi r^2 L S, \]

(1)

where \( \eta \) is the apparent viscosity, \( M \) is the tor-
que, $\alpha$ is the ratio of the diameter of stirrer to the inner diameter of crucible, $r$ is the radius of stirrer (practically the half-value of major axis), $L$ is the length of stirrer immersed in the melt, and $S$ is the rotation speed of stirrer.

The variation in torque during the solidification with rotation of stirrer at a high speed of 70 s$^{-1}$ in alloy C, D, E, F or G, which was prepared by addition of 0.3% of Fe, Ni, Ti, Mo or Cr to Al-22%Si-4%Cu system is shown in Fig. 5. A microstructure in the middle section cut transversely from alloy D, E, F or G rheocast at a rotation speed of 70 s$^{-1}$ is shown in Fig. 6. The same microstructures as seen in the middle transverse section of alloys D, E, F and G are observed in the top and bottom transverse sections of the alloys, because the same flow and cooling conditions of a solidifying alloy are accomplished at all positions of the alloy by the rotational stirring.

The reason for the occurrence of the difference in apparent viscosity among these alloys is considered as follows. Table 2 shows the cooling rate for a great part of the whole freezing range from the start of the solidification to just before the start of eutectics formation, and the size of primary silicon particles after the solidification. The primary silicon size is represented by the average value, $X$, and the standard deviation, $R$, under the condition of

Fig. 6 Microstructures in the middle section of alloys D to G rheocast with the rotation of stirrer at a speed of 70 s$^{-1}$. (a) Alloy D, (b) alloy E, (c) alloy F and (d) alloy G. Chemical composition of alloys D to G is listed in Table 1. Cooling rate from 100 K above liquidus to liquidus: 0.6 K/s.
residual error of $\sigma=5\%$. According to this, the cooling rates from the temperature for starting solidification to that for starting eutectics formation and the primary silicon particle size in alloy D, E or F are approximately equal to one another, so that the apparent viscosity in these alloys will have a middle level value of about 5 Pa·s. As alloy C has almost the same value of cooling rate but the small size of primary silicon particles as compared with the other alloys, the apparent viscosity in alloy C will decrease down to a value of 3.0 Pa·s. Since alloy G has almost the same size of primary silicon particles but the high cooling speed, in other words, the high crystallization rate of primary silicon, as compared with the other alloys, the apparent viscosity in alloy G will increase up to a value of 6.0 Pa·s. No significant difference in matrix can be found and inclusions hardly exist in every alloy even on a microstructural observation by an optical microscope with a higher magnification than in Figs. 3(b) and 6. As the degree of vacuum is restricted to below $1 \times 10^{-3}$ Pa during the present solidification of hypereutectic Al–Si alloys, the occurrence of oxides is scarcely observed. Therefore, the crystallization rate and size of primary silicon particles must be two main factors controlling the apparent viscosity.

4. Effect of grain refiners on microstructure

The influence of grain refiners of Na and Cu–P on the microstructure in hypereutectic Al–Si alloys rheocast at a high rotation speed and conventionally cast is investigated. An experimental result with addition of Na or Cu–P is shown in Fig. 7 or 8. Figure 7(a) shows a microstructure in conventionally cast alloy H containing 0.01% Na. Figure 7(b) shows a microstructure in alloy H rheocast at a rotation speed of 30 s$^{-1}$. The size of primary silicon particles in alloy H conventionally cast or rheocast at 30 s$^{-1}$ is 191±47 or 81±27 $\mu$m. Thus the rotational stirring at a speed of 30 s$^{-1}$ allows the primary silicon particle size to decrease below one half, since the primary silicon particles formed are partly

![Fig. 7 Microstructures in the middle section of alloy H modified with addition of 0.01%Na. (a) Conventionally cast and (b) rheocast at a rotation speed of 30 s$^{-1}$. Chemical composition of alloys I and J is listed in Table 1. Cooling rate from 100 K above liquidus to liquidus: 0.6 K/s.](image)
melted by the violent fluid flow with increased rotation of stirrer. It is also recognized that some primary silicon particles are aggregated like a chain by the turbulent flow. As the size of primary silicon particles in alloy C cast conventionally without addition of Na is 236 ± 49 μm as described above, it is observed that the size of primary silicon particles is likely to decrease only by addition of Na. Hanna et al. have melted an Al–16 mass%Si alloy with addition of 0.01% Na, have furnace-cooled the melt at a rate of 6.7 × 10^{-2} K/s, have found nucleation of secondary aluminum and eutectics upon primary silicon, and have decreased the primary silicon particle size below a value of 1 μm. This is an experimental fact for the considerable refinement of primary silicon particles and eutectics by modification with addition of Na in a stationary solidification. However, the special refining phenomenon found by Hanna et al. can not be observed in such a solidification with rotation of stirrer as in the present work. The reason for no refinement of microstructure by addition of Na is considered as follows. Thin films are formed in the surrounding region of primary silicon particles and become a barrier to restrain the primary silicon particles from growing in such a stationary solidification, but in the present rheocasting the thin films formed are destroyed by the turbulent flow with increased rotation of stirrer. Also the coarsening of eutectics is promoted by mixing diffusion with rapid rotation of stirrer, because the width of silicon phases in eutectics is decreased with supersaturation of silicon elements in other aluminum-rich phases in the eutectics by the turbulent mixing of the solidifying alloy at the final stage of solidification. Thus it is concluded that the effect of Na on the refinement of microstructure is completely avoided by the rotational stirring.

Figures 8(a) and (b) show the microstructure in alloy I rheocast at 30 and 70 s^{-1} with addition of 0.01%P, (b) at 70 s^{-1} with 0.01%P and (c) at 70 s^{-1} with 0.1%P. Chemical composition of alloys I and J is listed in Table 1. Cooling rate from 100 K above liquidus to liquidus: 0.6 K/s.
change in the primary silicon particle size can be found even with the increase in rotation speed of stirrer and content of addition.

The variation in apparent viscosity during the solidification with rotation of stirrer in alloy H or I with addition of Na or Cu–P is shown in Fig. 9. The apparent viscosity of the alloy remains almost unchanged during solidification except a rapid change at the initial stage of solidification. This rapid change in apparent viscosity is owing to the increase in rotation speed of stirrer from 18 to 30 or 70 s⁻¹ for an interval of 10 s from the start of solidification and to the irregularity of the nucleation and crystal growth of primary silicons. Subsequently, the values of apparent viscosity are clearly divided into two groups depending on the rotation speed of stirrer. At this time, the influence of grain refiners on the apparent viscosity in alloy C is not so conspicuous as the rotational speed. The apparent viscosity from the start of solidification in alloy C rheocast at 70 s⁻¹ remains almost unchanged at a value of 3.0 Pa·s. This value is slightly small as compared with a value of 3.4 Pa·s measured in alloy I rheocast at 70 s⁻¹ with addition of 0.01% P. A little depression in the apparent viscosity will be due to the addition of 0.01% P. The apparent viscosity in alloy H rheocast at 30 s⁻¹ has a value of 6.5 Pa·s. This value is considerably small as compared with a value of 7.9 Pa·s in alloy I rheocast at 30 s⁻¹. It is disclosed that Na is a more effective grain refiner for decreasing the apparent viscosity more than P, as the apparent viscosity from the start of solidification in alloy H rheocast at 70 s⁻¹ shows an almost constant value of 2.8 Pa·s.

5. Effect of rotation speed of stirrer on microstructure

The influence of rotation speed of a stirrer on the apparent viscosity and microstructure during the solidification with rotation of stirrer at high speeds in hypereutectic Al–Si alloys is investigated. As a result, the variation in apparent viscosity of alloy L rheocast at a stirrer speed of 30, 40 or 50 s⁻¹ for an interval from the start to the end of solidification is shown in Fig. 10. It is observed that the apparent viscosity is apt to decrease with increasing rotation speed of stirrer. In fact the apparent viscosity in alloy L rheocast at a rotation speed of 30 or 40 s⁻¹ remains almost unchanged at a value of 9.4 or 8.0 Pa·s during solidification except a rapid change at the initial stage of solidification. This rapid change of apparent viscosity is due to both the increase in stirrer speed from

![Fig. 9 Variation in apparent viscosity during the rotation of stirrer at a speed of 30 or 70 s⁻¹ from the start of solidification in alloys H and I. Cooling rate from 100 K above liquidus to liquidus: 0.6 K/s.](image1)

![Fig. 10 Variation in apparent viscosity during the rotation of stirrer at a speed of 30, 40 or 50 s⁻¹ from the start of solidification alloy L. Cooling rate from 100 K above liquidus to liquidus: 0.6 K/s.](image2)
18 to 30, 40 or 50 s\(^{-1}\) for an interval of 10 s from the start of solidification and the irregularity of the nucleation and crystal growth of primary silicons. Exceptionally a sudden transition in level of apparent viscosity from 5.4 to 3.6 Pa\cdot s\(^{-1}\) is observed at the middle stage of solidification in alloy L rheocast at a rotation speed of 50 s\(^{-1}\). The present authors explain this phenomenon as follows.—When a transformed stirrer with four smooth side walls and four smooth cut corners\(^6\) is rotated, four spaces originate in an instant between the wide four side walls of the stirrer and the semi-solid alloy. The spaces occurring between the stirrer and the alloy disappear immediately by an invasion of the flowing semi-solid alloy into the spaces. However, when the solidification of an alloy proceeds to some extent, the rotation speed of stirrer exceeds the velocity of semi-solid alloy flowing into the spaces in the solidification with rotation of stirrer at a speed of 50 s\(^{-1}\). Thus the semi-solid alloy can not wet the wide and smooth four side walls of stirrer in the subsequent process of solidification. As a result, since the semi-solid alloy keeps touch with only the narrow cut corners, the value of torque induced by the rotation of stirrer decreases as a matter of course and the value of apparent viscosity of an alloy rheocast at a rotation speed of 50 s\(^{-1}\) shows an abrupt depression to a level of 3.6 Pa\cdot s in eq. (1).

IV. Conclusion

Vacuum-melted hypereutectic Al–Si alloys are cooled at a rate of 0.6 K/s and agitated by the rotation of a stirrer at a high speed in the range from 30 to 70 s\(^{-1}\) from the start to just before the end of solidification. The results are summarized as follows.

1) The size of primary silicon particles in an Al–17.2\%Si or Al–22.9\%Si alloy ingot rheocast at 70 s\(^{-1}\) has an equivalent value of 89 ± 30 or 96 ± 34 \(\mu\)m. The primary silicon particle size in an Al–21.5\%Si–3.5\%Cu–0.1\%Fe–0.3\%Mg alloy is 66 ± 19 \(\mu\)m. This value is one third of a conventionally cast alloy ingot with the same composition as described above.

2) The apparent viscosity in an Al–21.5–21.7\%Si–3.5–3.7\%Cu–0.1\%Mg–0.3\%(Fe, Ni, Ti, Mo or Cr) alloy solidifying with rotation of stirrer at a speed of 70 s\(^{-1}\) remains almost unchanged at the following fixed level except a rapid change at the initial stage of solidification: A lower value of 3.0 Pa\cdot s in 0.3\%Fe alloy, a higher value of 6.0 Pa\cdot s in 0.3\%Cr alloy and a middle value of about 5 Pa\cdot s in the other alloys.

3) The size of primary silicon particles in an Al–20.4\%Si–3.5\%Cu–0.3\%Fe–0.1\%Mg alloy ingot rheocast at a rotation speed of 30 s\(^{-1}\) or conventionally cast with addition of 0.01\% Na is 81 ± 27 \(\mu\)m or 191 ± 47 \(\mu\)m. It decreases below one half only by the rotational stirring at a speed of 30 s\(^{-1}\) from the start to just before the end of solidification. The primary silicon particle sizes in an Al–20.6\%Si–3.5\%Cu–0.3\%Fe–0.1\%Mg alloy ingot rheocast at 30 or 70 s\(^{-1}\) with addition of 0.01\% P and rheocast at 70 s\(^{-1}\) with addition of 0.1\% P are 92 ± 31, 86 ± 29 and 81 ± 30 \(\mu\)m.

4) The apparent viscosity in the Al–20.6\%Si–3.5\%Cu–0.3\%Fe–0.1\%Mg alloy with addition of 0.01\% P solidifying with rotation of stirrer at a speed of 70 s\(^{-1}\) remains almost unchanged at a constant value of 3.4 Pa\cdot s except a rapid change at the initial stage of solidification. This value is slightly higher than a value of 3.0 Pa\cdot s measured in an Al–21.5\%Si–3.5\%Cu–0.3\%Fe–0.1\%Mg alloy with no addition of phosphorus. The apparent viscosity in the Al–20.6\%Si–3.5\%Cu–0.3\%Fe–0.1\%Mg alloy with addition of 0.01\% P solidifying with rotation of stirrer at a speed of 30 s\(^{-1}\) continues at a constant value which is comparatively higher than a value of 6.5 Pa\cdot s in the same alloy with addition of 0.01\% Na.

5) The apparent viscosity in an Al–15.4\%Si–4\%Cu–1.1\%Fe–0.3\%Mn–0.2\%Ti–0.02\%Zn–0.01\%Na alloy solidifying with rotation of stirrer at a speed of 30 or 40 s\(^{-1}\) remains almost unchanged at a fixed value of 9.4 or 8.0 Pa\cdot s except a rapid change at the initial stage of solidification. The apparent viscosity in the alloy solidifying with rotation of stirrer at a speed of 50 s\(^{-1}\) shows a sudden transition from 5.4 to 3.6 Pa\cdot s at the middle stage of solidification. The size of primary silicon particles in the alloy ingot rheocast at a rotation speed of 30, 40 or 50 s\(^{-1}\) is 101 ± 27, 96 ± 25 or 93 ± 25 \(\mu\)m.
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