Effects of static magnetic field and gas atmosphere on solidification of silicon by electromagnetic levitation

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Abstract. The effects of static magnetic field and hydrogen gas atmosphere on the solidification of silicon with hydrogen atom were examined using electromagnetic levitation method in hydrogen atmosphere. Since the convection in the levitated silicon melt which is caused by the electromagnetic field is restrained by a high static magnetic field, it is possible to examine a solidification of silicon from an equilibrium silicon melt with hydrogen without an influence of convection. The cooling rate of the melt increases with increasing hydrogen partial pressure. Since the undercooling of the melt does not change with the static magnetic field, the grain size on the surface does not change with the static magnetic field. However, the morphology of the grain surface drastically changed from flat and smooth to undulation.

1. Introduction
A containerless process such as electromagnetic levitation is useful to study of rapid solidification from the melt [1,2]. When a high static magnetic field is applied for the levitation process and the convection in the levitated melt which is caused by electromagnetic field is restrained by strong Lorentz force from the static magnetic field, the convection in the melt can be ignored, namely, the melt can deal with a rigid body [3]. A rigid body consisted of liquid phase is convenient to measure the thermophysical properties of the melt [4,5] and the solidification from a rigid body is suitable to examine an effect of convection on the solidified structure. Yasuda et al. suggest that the microstructure of carbon steel changes from equiaxed grain to columnar grain by static magnetic field application from 0 to 10 T because of inhibition the fragmentation of dendrite arm by the convection during the solidification [6]. When silicon is solidified by electromagnetic levitation method in high static magnetic field in hydrogen atmosphere, it is expected that an equilibrium silicon melt with hydrogen except an effect of convection in the melt is obtained.

In this work, the solidification of silicon was performed by electromagnetic levitation method at high static magnetic field of 0-5 T in 25%H2-75%Ar and 50%H2-50%Ar mixed gas in order to examine the effects of static magnetic field and hydrogen atmosphere on the solidification of silicon with hydrogen atoms.
2. Experimental procedure

0.8 g of silicon with 99.999% purity was used for the solidification. Silicon bulk was put on a quartz dish in spiral induction heating coil and was heated by a semiconductor laser with wave length of 808 nm. Then, the silicon melt was levitated in the spiral induction coil as shown in Fig.1. When the silicon was completely melted, the temperature correction for the monochrome pyrometer was performed by adjusting the melting point of silicon 1685 K. Then, H₂-Ar mixed gas or Ar gas was introduced in the chamber up to 0.1 MPa. The melting condition kept at 1773 K for 0.6 ks. Then, the power of the spiral induction coil turns up to a constant value of 38 A to move the silicon melt sphere at a fixed position of upside the spiral induction coil for cooling the melt. After solidifying of the surface of the sphere, the sample was caught by the quartz dish and the power of the induction coil was switched off. The solidification was monitored by a CCD camera from top of the chamber.

![Diagram of experimental setup](image)

Figure 1  Apparatus for electromagnetic levitation furnace.

3. Result and discussion

Kobatake et al. suggested that the thermal conductivity of liquid silicon in static magnetic field of 2-4 T shows a constant value [4]; the convection in the levitated silicon melt due to the electromagnetic field is restrained by strong Lorentz force from the static magnetic field. Hence, in the present study, the solidification was performed under a static magnetic field of 5 T which is enough to restrain the convection in the melt. Since the hydrogen diffusion coefficient in solid silicon at the melting point is in order of 10⁻⁴ cm²/s [7] and the diameter of melt sphere is about 0.8 cm, it is considered that the holding time of 0.6 ks is enough to make an equilibrium state of silicon melt with hydrogen. The temperature measurement error was within 10 K.

Figure 2 shows the cooling curves of the melts where, the static magnetic field is controlled to 5 T. The cooling rate of the melt for the case of the melting in 50%H₂-50%Ar is larger than that for the case of the melting in 25%H₂-75%Ar. Since the thermal conductivity of hydrogen gas is larger than that of argon gas, the cooling rate of the surface increased with increasing hydrogen partial pressure.
Figure 3 shows the dependence undercooling of the melts. The undercooling did not change with the static magnetic field. Yasuda et al. reported that the undercooling of copper alloy varies from 0K to 300K and does not depend on the static magnetic field [6]. On the other hand, the undercooling of pure copper melt varies from 0K to 100K [6]. In the present study, the undercooling of the melts varies less than 50 K and has a constant value with the static magnetic field. Hence, it can be seen that silicon melts with hydrogen atoms acts like a melt of pure metals.

![Fig.2 The cooling curves of the melts where, the static magnetic field is controlled to 5 T.](image1)

Since the undercooling of the melt does not change with the static magnetic field, size of the surface grains as shown in Fig.4 does not change with the static magnetic field as shown in Fig.5. However, the morphology of the grains surface changes with the static magnetic field from flat and smooth to undulation as shown in Fig.5. Small undulation is formed on individual grain surface for the sample solidified at 3 T. On the other hand, a facet crystal is appeared on the grain surface for the sample solidified at 5 T. This result suggests that the static magnetic field effects on the solidification of silicon, especially, on the nucleation of crystal.

![Fig.4 The morphology changes of the grains surface with the static magnetic field.](image2)
4. Conclusion
Solidification from an equilibrium silicon melt with hydrogen was carried out by an electromagnetic levitation method under high static magnetic field. The cooling rate of the melt for the case of the melting in 50%H₂-50%Ar is larger than that for the case of the melting in 25%H₂-75%Ar. The static magnetic field affects on the solidification of silicon, especially, on the nucleation of crystal.

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