Effect of liquid volume on the evolution of solidified structure in horizontal centrifugal casting

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Abstract. Horizontal centrifugal casting process is widely applied for long products. However, it often has macro-segregation problems, such as band segregation. In order to understand solidification process in this process, in-situ observation using transparent substances has been performed. Here, the effect of liquid volume in the mold was investigated. Succinonitrile-water alloy was introduced in the glass cell and filling ratio of organic alloy was varied from 70 to 100 vol. % and the rotation rate was set to be 250 rpm. Equiaxed grains formed in case of low filling ratio. On the other hand, no equiaxed grain formed when the filling ratio was 100 vol. %. Strong fluid flow may be induced by the fluctuation of free surface and this may form equiaxed grains. However, when the area of free surface decreased with increasing filling ratio, the influence of free surface diminished and fluid flow was stabilized. Therefore, well-developed columnar zone grew and no equiaxed grains formed.

1. Introduction

Horizontal centrifugal casting is widely used for production of pipes, rolls and so on. Advantage of this process is to press molten metal against the permanent mold wall due to centrifugal force. Owing to this force, fine solidified structure and sound castings without porosity and/or non-metallic inclusion can be obtained [1]. On the other hand, there are sometimes problems of macroscopic segregation. The countermeasure to the segregation problems has not been established because the formation mechanism of macroscopic segregation is still unclear. Further, solidification process is not well understood [2-4] because the centrifugal casting itself is essentially dynamic process.

Thus, an experimental technique of in-situ observation using succinonitrile-water alloy system for horizontal centrifugal casting process using an organic substance has been developed by the present authors [5-7]. Here, an important result was unveiled, such as the oscillation of equiaxed grains synchronizing to rotation of mold and violent fluid flow due to fluctuation of free surface. Especially, the vigorous and unsteady fluctuation of free surface may form equiaxed grains and make them oscillate back and forth. Therefore, in this study, in order to understand the effect of free surface on...
the evolution of solidified structure, in-situ observations have been made changing the liquid volume in the glass cells.

2. Experimental Procedure
In order to make an in-situ observation of horizontal centrifugal casting, basically the same equipment as the previous study was used \([5,6]\). A schematic view of experimental apparatus is shown in figure 1. A glass cell, which contained succinonitrile-water alloy, was vertically set along the rotating axis. The glass cell, 100 mm in outer diameter and 1.3 mm gap, was constructed from two pieces of round glass and some small pieces of glass with epoxy resin. Here, the filling ratios were varied from 70 to 100 vol.%. A high vision video camera was installed on the rotating shaft to make an in-situ observation. Since the frame rate was 30 frames per second, rotation speed was limited to 250 rpm. One of the biggest advantageous points was that the camera for in-situ observation rotates with the glass cell. Thus, what is rotating with the mold, it is stationary in the movie. On the other hand, what is moving relative to the mold, it is moving in the movie.

Using this system, one could observe the evolution of solidified structure. The observed area was approximately 40 mm x 50 mm. Basically, the solidification proceeded inwards from the outer surface, since a positive temperature gradient was imposed. In this study, rotation rate was fixed to be 250 rpm, which corresponded to 3.5 G at the outer surface of the glass cell.

3. Experimental Results and Discussions
3.1. Solidification Process
When the filling ratio was 70 vol.%, the snap shots of in-situ observation are shown in figure 2. The interval of each snap shot was 7 seconds. Since figure 2 a) is the initial stage of solidification, the major part in the glass cell was liquid phase. The glass cell holder (the left hand side) was formerly cooled by water, the solidification started from the outside of the glass cell. In this snap shot, ‘white part’ is the solid phase and transparent part is the liquid phase. Here, the columnar dendrite, which grew from the outside of glass cell, was observed and some solid particles (equiaxed grains) are visible near the solid/liquid interface. Furthermore, the free surface was also observed on the right hand side.

![Figure 1. A schematic drawing of experimental apparatus for horizontal centrifugal casting.](image-url)
Equiaxed grains formed much and they stopped the growth of columnar dendrites. Equiaxed grains are observed near the columnar zone and in this snapshot there is no equiaxed grain near the free surface, because it is still in the initial stage of solidification (figure 2 b)). Then, in all region of the liquid phase, so many equiaxed grains were formed (figure 2 c)). Here, almost all equiaxed grains were independent and moved up and down synchronously in the observed area. Free surface fluctuated or violently moved according to the rotation. Figure 2 d) shows a further elapsed snapshot. Here, the volume fraction in the mushy zone increased and the movement of equiaxed grains calmed down because the apparent viscosity of solid/liquid mixture increased. Thus, the shape of free surface gradually became a circle. There are some dark spots, where the solid fraction was lower than the other area. They may result in the segregation spots.

![Snapshots](image1.png)

**Figure 2.** Snap shots of in-situ observation of horizontal centrifugal casting at a rotation rate was 250 rpm. The filling ratio was 70 vol.%.

When the filling ratio was 100 vol.%., the snapshot of in-situ observation are shown in figure 3. The interval of each snapshot was 15 seconds. The columnar dendrites started to grow from the outside of the glass cell, which is the same as shown in figure 2a). The columnar dendrites continued to grow inward and no equiaxed grains formed (figure 3 b) - d)). Columnar dendrites with favored growth direction grew faster and they were selected via grain selection.

![Snapshots](image2.png)

**Figure 3.** Snap shots of in-situ observation of horizontal centrifugal casting at a rotation rate was 250 rpm. The filling ratio was 100 vol.%.

3.2. Equiaxed zone ratio

The areal fraction of equiaxed zone was measured in the observation area. The relationship between the filling ratio and the areal fraction of equiaxed zone is shown in figure 4. When the filling ratio is
less than 80%, the equiaxed zone ratio is constant and approximately 80%. The area of the columnar dendrite was very small. Almost all inner regions consist of equiaxed grains. The areal fraction of equiaxed zone decreased steeply with increasing the filling ratio. When the filling ratio was 100%, solidified structure consists of columnar dendrites and no equiaxed grains are formed.

3.3. Liquid flow pattern affected by free surface

In order to understand the liquid flow pattern, model experiments have been performed. The glass cell was filled with silicone oil and small plastic particles. The filling ratio of silicone oil was 70 and 100 vol.%. The kinematic viscosity of silicone oil was 5 cSt and the density of plastic particles is slightly larger than the silicone oil. These glass cells were set in the glass cell holder and in-situ observation were carried out at a rotation rate of 250 rpm. The locus of a particle was analyzed to characterize the fluid flow in the horizontal centrifugal casting.

![Figure 4](image)

**Figure 4.** Relationship between the filling ratio and areal fraction of equiaxed zone.

![Figure 5](image)

**Figure 5.** Loci of a plastic particle in the model experiment for horizontal centrifugal casting process.

a) the filling ratio was 70 vol.%
b) the filling ratio was 100 vol.%

The experimental results are shown in figure 5. Figure 5 a) indicates the locus of the particle in case of the filling rate of 70 vol.%. The particle moved up and down, indicating elongated circles and traveled toward the anti-rotating direction. Furthermore, it moved little by little towards the radial direction due to centrifugal force. On the contrary, in case of the filling ratio of 100 vol.%, the locus...
of the particle is shown in figure 5 b). The plastic particle moved outwards, indicating small circles. No traveling towards the anti-rotating direction was observed. Small vibration is due to gravitational acceleration. The amplitude of vibration in case of the filling ratio of 70 vol.% is larger than that in case of the filling ratio of 100 vol.%. This may be attributed the effect of free surface. The fluctuation of free surface may enhance the movement of plastic particles or equiaxed grains. When the filling ratio is 70 vol.%, traveling toward the anti-rotating direction was observed. On the other hand, when 100 vol.%, this movement was not observed. The difference between these two conditions is presence of free surface. Therefore, travelling towards the anti-rotating direction may be also caused by the fluctuation of free surface.

In the model experiment using silicone oil and small plastic particles, the particles clearly moved gradually outward. The reason of this is acceleration in radial direction due to centrifugal force. In the in-situ observation using succinonitrile-water alloy, it was difficult to observe the outward movement of equiaxed grains. Since the solidification proceeds from outside to inside, there is no room for equiaxed grain to move outward.

4. Conclusions
The experimental study for in-situ observation of horizontal centrifugal casting process has been performed changing the filling ratio in the glass cell. Following conclusions have been derived.
1) When the filling ratio is low, liquid phase or solid/liquid mixture not only vibrates but flows because of the fluctuation of free surface. In this case, equiaxed grains form because of vigorous flow.
2) When the filling ratio is 100%, liquid phase vibrates but does not flow. Equiaxed grains do not form because there is no macroscopic and vigorous flow in the liquid phase.

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