Effect of cooling rate on the porosity defect in the thick aluminum casting by 3D computed tomography analysis

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Abstract. In the present study, effect of cooling rate on the formation of the porosity in the thick aluminum sand casting was investigated. Nowadays large scale thick aluminum casting replaces steel frame for vacuum chamber for semiconductor production, with the consideration of weight and cost reduction. Several thick aluminum castings were manufactured using chill with temperature measurements. The castings were inspected by using 3D computed tomography in order to quantify the porosity defect density in the castings. Effect of the thickness of the chill on the porosity defect density were discussed.

1. Introduction
Vacuum chambers for manufacturing solar cells, LCD display and semiconductors are fabricated by cutting and machining of steel or aluminum plate and welding with them. This costs too much time and money, so it will be very important to reduce the cost for vacuum chamber manufacturing. Nowadays machining and welding process are replaced with sand casting process. When the sand casting is applied to manufacturing large vacuum chamber rather than machining and welding, over 40% cost reduction is possible [1]. However in the cast products, gas defects inside the casting can be leaked during operating the vacuum chamber, the casting technique minimizing the gas defect and inclusions inside the casting and its inspection technique is necessary. Generally large cast product has thick walls, therefore cooling is crucial for taking sound castings. Chills are usually used for accelerating cooling rates, and have several advantages as follows

- Smooth melt feeding to shrinkage cavities
- Increase of temperature gradient
- Fine grain structure
- Decrease of dendrite spacing
- Decrease of large shrinkage cavities

When the molten aluminum solidifies, solubility of hydrogen in the melt is decreased and gas porosities are formed. When chills are applied, fast cooling rates can be obtained and gas in the melt is supersaturated. This avoids nucleation of gas porosity, so amount of gas porosity can be minimized.
Traditionally, there have been many studies on the shrinkage cavity of products according to cooling rate in aluminum casting process [1]. Internal defects of casting product were analyzed using industrial CT (Computed Tomography) [2] and a series of studies have been carried out by Kwak [3, 4] to evaluate the mechanical strength of fatigue and impact according to defects which were detected through CT. However, since the cooling rate depends on the location in the product, its characteristics also vary in the distribution of the cooling rate proportionally. Therefore, it is very important to obtain temperature distributions during cooling in the product. In this paper, an investigation was carried out the temperature history of the A356 cast aluminum alloy specimen of 40 mm thickness used for the vacuum chamber by varying the thickness of the chill and the simulation for the temperature history.

### 2. Experimental Method

#### 2.1 Preparation of specimens by casting experiment

In the present study, size of 200x150mm with 40mm thickness specimens were cast. As shown in Fig. 1. With computer simulation, gates and risers is found to be properly designed to obtain sound casting with no shrinkage defects.

![Figure 1. Schematic diagram of specimen and its casting design.](image)

The chill material was SS400 steel and the thickness was 40mm, 60 mm, and 80 mm (hereafter 40T, 60T, 80T, respectively). The surface of the chill is machined with knurled shape, in order to provide more contact area than that of flat surface chill between casting and sand mold, as shown in Fig. 2. The position of the thermocouple was 10mm from the chill, same position with that of porosity defect analysis. In order to obtain the temperature distribution of the casting, 6 thermocouples are installed inside the mold cavity, and the temperature is measured during casting.

![Figure 2. (a) Schematic diagram of knurl shaped chills and (b) thickness of the chills and the position of the thermocouple and chill.](image)

A356 alloy was used for casting materials and compositions were shown in Table 1.
Table 1 Chemical composition of A356 proposed in the present study

|   | Al  | Si  | Fe  | Cu  | Mg  | Ti  |
|---|-----|-----|-----|-----|-----|-----|
| wt%| 92.5| 7.0 | 0.09| 0.002| 0.35| 0.12|

Fig. 3 shows the photograph of castings in the present study. Knurl shape in the bottom of the casting was designed in order to achieve good contact of the casting and mold.

![Photograph of castings](image1)

Figure 3. Photographs of the casting used in the present study.

2.2 Analysis by simulation and computed tomography (CT)
In order to investigate the relationship between cooling rates and porosity in the specimen, computer simulation analysis and 3D industrial CT was used. For the simulation of the casting process, in-house developed Z-Cast software is used, and Rayscan 250E CT system is used for CT scan and in-house developed VX3D software is used for porosity analysis. Fig. 4 shows the photograph of Rayscan 250E and VX3D used in the present study.

![Photograph of CT system and analysis software](image2)

Figure 4. Photographs of Rayscan 250E CT system and VX3D analysis software.

3. Result and Discussions

3.1 Cooling Rate by Experiment & Numerical Data
Fig. 5 shows experimental cooling curves for chill thickness 40T, 60T, and 80T. Fast cooling and short solidification time was found when the chill thickness increases. Since it is difficult to install thermocouples in all areas of the specimen, the numerical conditions for heat transfer analysis those can simulate temperature history correspond to the thermocouple experimental data was set. Then the cooling rates for each area inside the product were obtained through the heat transfer analysis. Fig. 6 shows the experimental and numerical values at the thermocouple location 1 in Fig. 7. The vertical positions of cooling rate analysis in the specimen are 10 mm, 20 mm,
and 30 mm from the chill, and each positions are located horizontally from 12.5mm (position 2, 4, 6) and 37.5mm (position 1, 3, 5) from the right edge of the chill, as shown in Fig. 7. The simulation and experiment cooling curves is shown to be a relatively good agreement.

Figure 5. Cooling curves after pouring with chill thickness variance.

Figure 6. Cooling curves after pouring at thermocouple location 1

Figure 7. The locations of thermocouples for simulated cooling rate analysis.

The cooling rate can be evaluated as the temperature interval divided by the cooling time to 542°C from 613°C which are the solidus and liquidus temperatures of A356. Fig. 8 shows cooling curves for every 6 positions in the casting in the case of using 40T chill, by simulation analysis. The fastest cooling rates is found in the thermocouple position 1, and then 3 → 5 → 2 → 4 → 6. The slowest cooling rates is shown in the thermocouple position 6.
The cooling rates of all specimens are listed in Table 1. The position 1 of 80T has the fastest cooling rate of 0.266°C/sec, and the position 6 of 40T was the slowest at 0.088°C/sec. As shown in Table 2, when comparing the cooling rates according to the thickness, 60T and 80T shows relatively similar cooling rates, but they were different from 40T. It is considered that maximum chill thickness for maximum cooling rate will be 60T.

### Table 2. Cooling rate according to thickness of chill

| No | Cooling Rate [°C/sec] |
|----|-----------------------|
| 40T | 60T | 80T |
| 1  | 0.158 | 0.257 | 0.266 |
| 2  | 0.098 | 0.184 | 0.196 |
| 3  | 0.125 | 0.210 | 0.220 |
| 4  | 0.094 | 0.171 | 0.182 |
| 5  | 0.118 | 0.193 | 0.202 |
| 6  | 0.088 | 0.168 | 0.179 |

3.2 Comparison of 3D CT results with chill thickness and cooling rate

Figure 10 shows an example of porosity analysis. Table 3 shows the amount of porosity and average diameter in the specimens. With the chill thickness of 40T, it is found the amount of porosity is averagely 0.23%, whereas 60T for 0.039% and 80T for 0.017%. Average diameter of the porosity is 0.42mm for 40T, 0.36mm for 60T and 0.35 for 80T. It is considered that the thin chill thickness would have larger amount of porosity.
Table 3 Amount and average diameter of the porosity in the specimens

| TC Position | 40T | 60T | 80T |
|-------------|-----|-----|-----|
|             | porosity [%] | Avg. Diameter [mm] | porosity [%] | Avg. Diameter [mm] | porosity [%] | Avg. Diameter [mm] |
| 1           | 0.1484 | 0.39 | 0.0045 | 0.36 | 0.0016 | 0.32 |
| 2           | 0.1793 | 0.39 | 0.1163 | 0.36 | 0.0094 | 0.33 |
| 3           | 0.1346 | 0.41 | 0.0065 | 0.33 | 0.0148 | 0.38 |
| 4           | 0.1703 | 0.41 | 0.0263 | 0.36 | 0.0115 | 0.36 |
| 5           | 0.5218 | 0.48 | 0.0793 | 0.40 | 0.0524 | 0.37 |
| 6           | 0.2564 | 0.42 | 0.0054 | 0.35 | 0.0126 | 0.35 |
| Avg.        | 0.2351 | 0.42 | 0.0397 | 0.36 | 0.0170 | 0.35 |

Fig. 10. Example of porosity analysis of the specimen.

Fig. 11 shows relationship of porosity with cooling rates. In the case of chill thickness 60T and 80T, porosity percentage is found to be below 0.1%, otherwise more than 0.1% porosity is found in the case of 40T. Chill thickness of 60T and 80T shows the cooling rate to be above 0.16°C/sec, so faster cooling rate than 0.16°C/sec is desirable to acquire less porosity below 0.1%.

4. Summary
It was not realistic to measure the temperature histories by installing thermocouples in all areas of the specimen. Therefore, the heat transfer analysis combined with the thermocouple temperature history data was performed to obtain the cooling rate distributions for the whole specimens. In case of 40mm aluminum block, 40 mm chill and 60mm chill were different at cooling rate, but the difference between 60mm and 80 mm was small. The cooling rate distribution inside the specimens could be obtained by
using the commercial casting process analysis program Z-Cast. And it can be used to analyze the correlation between the metallographic or defect distribution results and the cooling rate.

5. Acknowledgments
This work was supported by the Ministry of Trade, Industry and Energy (MOTIE, South Korea) [Project Name: Development of large-scale high-quality aluminum sand casting technology].

6. References
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