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Effect of Grain Refining on the Shrinkage Porosity in Thin-Walled Plates Produced by Investment Casting Integrating Controlled Solidification Technique

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Abstract. The production of high integrity thin-walled investment cast components can be achieved by controlling the solidification process. The aim of this work was to study the effect of grain refiner on thin-walled aluminum alloy A356.0 plates produced by investment casting using a controlled solidification process. Moulds with plate thicknesses of 0.7 mm, 1.5 mm and 2 mm were cast. The A356.0 alloy was melted in an electric resistance furnace, one mould was cast with controlled solidification process, second mould was cast using A356.0 modified with Strontium (Sr) (0.03%), grain refiner Aluminium Titanium Boron (Al-5Ti-B) (0.11%) and controlled solidification process. Melt temperature was stabilized at 700 °C before being poured into the mould at 740 °C. Moulds were inserted into a cooling medium at a controlled rate until the plates were submerged and held submerged for few minutes before being withdrawn. The microstructure and shrinkage porosity were assessed using optical microscope and the density was measured using the Archimedes principle. Qualitative assessment of the shrinkage porosity was measured using Image J software. Grain refinement was shown to reduce the size of primary dendrites. Shrinkage porosity decreased in samples. This was supported by the higher density observed for the grain refined casting.

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1. INTRODUCTION

During conventional investment casting [1] of aluminium alloys, shrinkage porosity forms at interdendritic regions during solidification process if there is no liquid alloy available to feed the solidification front. Controlled solidification technique [2] , [3] has been used together with grain refining process [4] to reduce the shrinkage porosity in castings. Modification of high silicon (Si) alloys is performed to refine Si particles morphology in the eutectic phase. At very thin wall thickness level, cooling rate tends to be high and leads to high shrinkage velocities, as the speed goes above the threshold shrinkage velocity then pores will form, and very limited time given for diffusion to take place hence porosity is formed whether you have a grain refiner or not [5]. Even though thickness level below 2 mm possess high driving force nucleation, which may lead to finer grains [6] that should have been in assistance to promote good feeding at interdimeric regions [7], you also have high shrinkage velocities which leads to shrinkage porosity. The alternative solutions are to reduce the cooling rate by increasing the cooling medium temperature, this will improve feeding and reduce shrinkage velocities. [7,8].

The current study was conducted with the assumption that gas content in the melt was constant for both the grain refined and unrefined aluminium alloys. The aim was to evaluate the impact of grain refiner on the porosity levels, in particular shrinkage porosity, using a controlled solidification process.

2. METHODOLOGY

Two wax trees assembled, ceramic moulds created by dipping the wax assembly in to two different slurries which are the primary and backup slurries. Primary slurry consists of colloidal silica binder and zircon (Zr) powder, while the backup slurry consists of colloidal silica binder and fused silica powder. Stucco for primary coat is zircon (Zr) sand and for back-up slurry is fused silica sand. Moulds were created, dried in a temperature and humidity-controlled environment. Casting with three thicknesses of 0.7 mm, 1.5 mm, 2 mm were produced. The casting process summarised in Figure .1 encompassed melting and holding the aluminium alloy A356.0 at a casting temperature of 700 °C and no degassing was performed. Mould temperature of 730 °C, modifying the alloy and the immersing the mould into the cooling medium at a constant rate. Prior to pouring the molten alloy into the mould, it was modified using Al-15Sr master alloy to achieve a nominal Sr content of 0.03 wt.% and grain refined with Al-5Ti-B grain refiner master alloy to achieve a Ti content of 0.11wt.% in the grain refined casting. The mould filled with the molten alloy was submerged in the cooling medium at a constant speed and held for 10 minutes before being withdrawn. Samples were taken at the top of each plate thickness and analysed as shown in Fig.2. Metallographic samples were prepared and analysed using optical microscopy (OM) and image software, was used to estimate the shrinkage porosity levels. The density of the cast plates was evaluated using the Archimedes Method. [9] Plates dimensions: Height is 150 mm, width 30 mm. Runners: 300 mm x 10mm x 10 mm. Sprue: 25 mm x 20 mm x 280 mm. height of the Mold is 380 mm.

Fig. 1: Casting process flow diagram

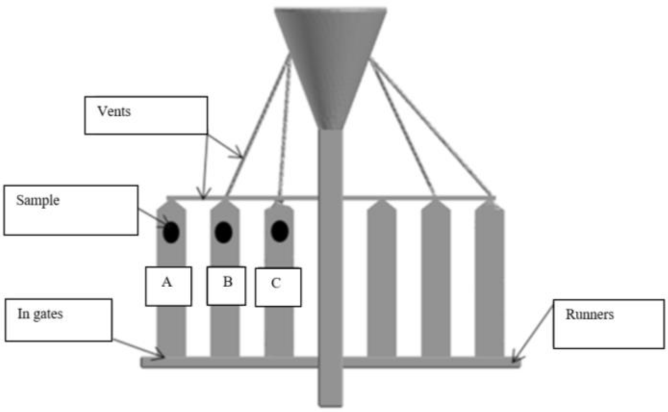


Fig. 2 Sampling regions and wax pattern mold CAD file. (A = 2 mm; B = 0.7 mm; C= 1.5 mm plate

3. RESULTS AND DISCUSSIONS

Two cast moulds complete filled, three thicknesses of 0.7 mm, 1.5 mm and 2 mm are shown in Figure 3. One mould was cooled with liquid bath cooling technique and without grain refining (A), the other with grain refining as well as modification (B).

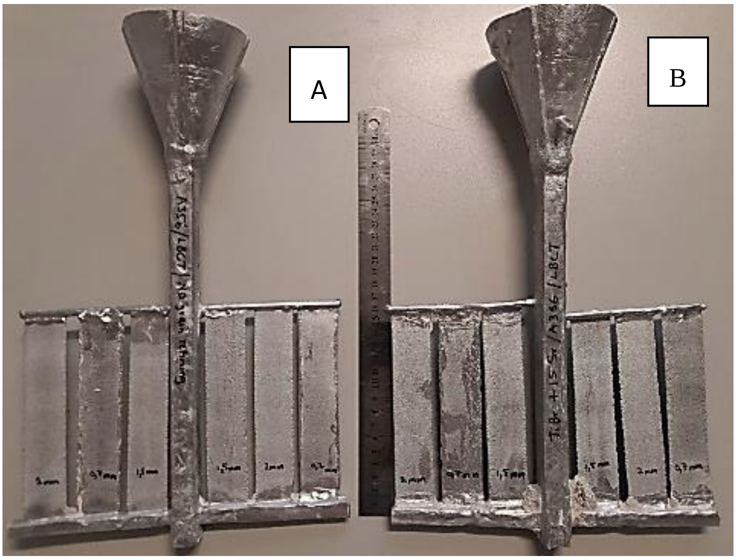
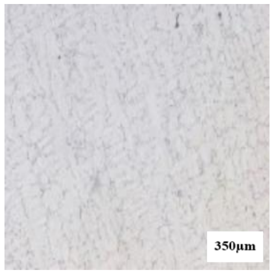


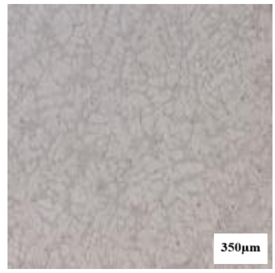
Fig. 3. Two moulds cast with investment casting, grain refined with Ti-B, modified with Sr, then cooled with control solidification technique

It can be seen in Fig. 3 that complete filling of the mould with various wall thicknesses from 2 mm down to 0.7 mm wall thickness was achieved. This demonstrated the capability of the process to fill relatively thin wall thicknesses with no flow defects and premature solidification that can cause incomplete filling. This does not preclude the formation of gas and shrinkage porosity which can occur due incorrect melt practice and lack of control of the solidification process. Shrinkage porosity can be eliminated by optimisation of the process parameters and modification of the alloy to influence the solidification characteristics.

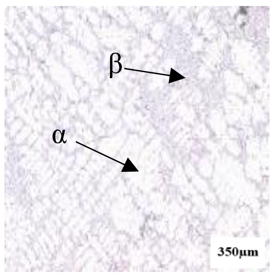
This study investigated the effect of grain refining and controlled solidification on shrinkage porosity. The morphology of the primary alpha and the silicon particle in the eutectic regions for grain refined and unrefined castings are shown in Fig. 4. The casting, which was not grain refined as shown in Fig 4A has microstructure of columnar dendritic grains with relatively fine dendritic arm spacing due to the high cooling rates. The columnar grains were much finer for the 0.7 mm thick plate compared to the 1.5 mm and 2 mm plates, respectively. This is consistent with the expected higher cooling rate for the thinner plates. The grain refined casting revealed shorter columnar dendrites with similar dendritic arm spacing. The formation of long coarse dendrites limits the flow of molten metal in the interdendritic zones, hence causing the formation of shrinkage porosity. The grain refining effect stimulates a higher volume of nuclei which results in shorter columnar grains and easier feeding of the interdendritic zones. This combined with the higher cooling rate due to the quench effect of the cooling medium will facilitate a reduction in shrinkage porosity. Fig 4. D, E and F show a mixture of shorter dendrites, some round primary alpha(α) grains and refined eutectic phase (β)



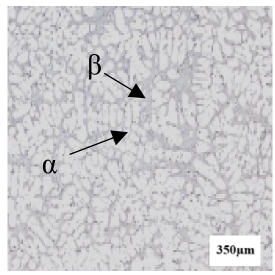
(A) 0.7 mm



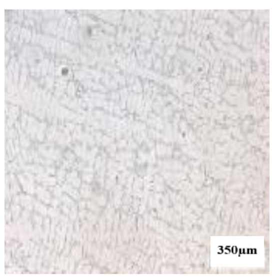
(D) 0.7 mm



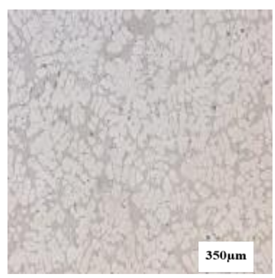
(B) 1.5 mm



(E) 1.5 mm



(C) 2 mm



(F) 2 mm

Fig. 4. Morphology of primary alpha is observed on the LBCT – without grain refining (A, B, C). as well as on LBCT – Grain refined and modification. (D, E, F)

The refined primary dendrites should assist in promoting shorter travel routes for molten liquid metal during solidification process. By decreasing this travel routes around the grains for molten aluminum alloy A356 .0 we can better fill at inter dendritic regions.

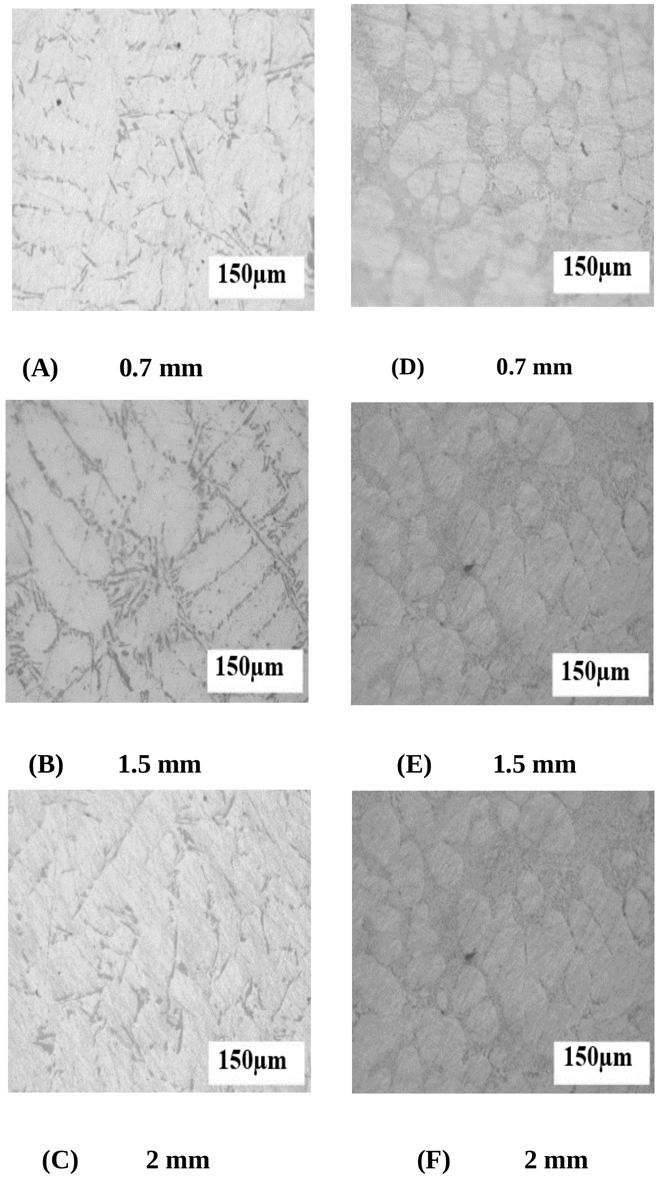
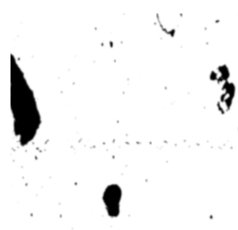


Fig. 5. Morphology of primary alpha is observed on the LBCT – without grain refining (A, B, C). as well as on LBCT – Grain refined (D, E, F). Effect of strontium on the morphology and size of Silicon particle on eutectics (150um remember)

The fine silicon particles morphology and sizes on the eutectic region, Fig.5, was typical of the influence of addition of eutectic modifiers, in this case strontium. The higher magnification show clearly that the primary alpha morphology changed to a mixture of round grains and shorter dendrites, see Fig 5. Due to grain refining. Volume fraction of pores was estimated from 2D micrographs. Fig. 6, showed a reduction in shrinkage porosity between samples cooled by only controlled solidification process and those from controlled solidification technique, grain refining and modification. While grain refining is expected to reduce the shrinkage porosity, care must be exercised with certain thinner sections, at this level shrinkage

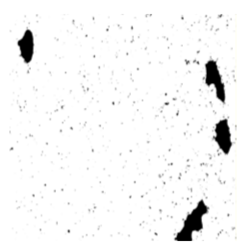
velocity also needs to be considered. Shrinkage velocity is directly proportional to the cooling rate. Thin sections tend to have high cooling rate and this result in higher shrinkage velocities. Once the latter get above the threshold, shrinkage porosity will form [6]. The density measurements, Fig. 7, shows that gas and shrinkage porosity exist in both the grain refined and unrefined castings. The grain refined casting did show a slightly increase in density and this was attributed mainly to a reduction in the amount of shrinkage porosity based on the assumption that the gas porosity levels remained constant since the same batch of aluminium alloy ingots was used for both castings. Grain refiner had the greatest influence on reducing shrinkage porosity in the 2mm plate, but it was unable to eliminate much shrinkage porosity in the 1.5mm and 0.7mm plates.

(A) 0.7 mm; 12.79%



(D) 0.7 mm: 5.12%

(B) 1.5 mm; 17.89%



(E) 1.5 mm; 4.3%

(C) 2 mm; 12.17 %

(F) 2 mm; %5.5 %

Fig. 6. volume fraction analysis on 2d micrographs, focusing on clusters of pores. (A, B, C- no grain refiner); (D, E, F – with grain refiner)

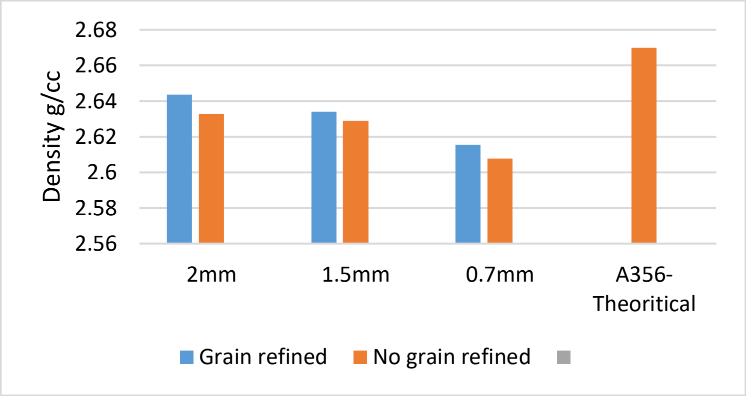


Fig. 7. Density measured of three plate thicknesses compared to theoretical density

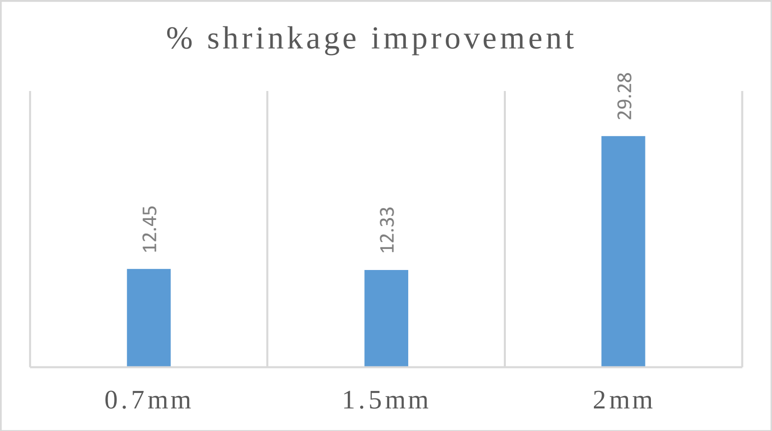


Fig. 8 . Shows difference in densities of three plate thickness.

4. CONCLUSION

1. Filling of thin plates, 0.7 mm, 1.5 mm,2 mm was successful with grain refiner and without grain refiner
2. The morphology of primary alpha was changed from long dendritic to round and shorter dendrites by grain refining effect.
3. Morphology of silicon particle in the eutectic regions was changed from coarse long needle like shape to small rounds shape and finely dispersed.
4. The size pores on sample with grain refiner are smaller and occupy lower volume fraction in 2D micrographs compared to samples without grain refiner and modification
5. Grain refining is beneficial on thicker samples e.g., 2 mm at the current process parameters
6. Components with wall thickness less than 2 mm did not benefit from grain refining and modification in terms of reducing shrinkage porosity

This preliminary investigation has shown the potential for use of grain refiner with the combination of controlled cooling to reduce shrinkage porosity. However, further work needs to be conducted on optimizing processing parameters from melting practice to control the cooling process to reduce both gas and shrinkage porosity further.

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