Investigation of Refining Processes that Improve Liquid Metal Quality in Aluminum Production

ABSTRACT ***:*** *In this study, the effects of melting and refining processes used in the production of aluminum alloys on the quality of liquid metal were investigated. The impact of oxide compounds encountered during aluminum processing on the quality of the liquid metal and the effectiveness of refining processes aimed at removing these oxide compounds were examined. The study involved four different casting samples made from 6060 alloy, where the effects of flux amounts, cleaning times, and nitrogen gas pressure on the quality of the liquid metal were explored. To assess the quality of the liquid metal, the density index (DI%), bifilm index (BI), and hydrogen level (ml/100 g Al) were analyzed using the solidification under vacuum (RPT) method. Microstructural examinations, including parameters such as grain size, grain count, and homogeneity ratio, showed that the best liquid metal quality was achieved with a flux amount of 1.42 kg/ton and a gas removal time of 4.16 kg/min. These results emphasize the importance of optimized flux usage and gas removal times in improving the quality of liquid metal in aluminum production.*

KEYWORDS-*Melt Quality, Solidification, Flux, Microstructure, 6060 Alloy*

I. INTRODUCTION

Aluminum is a metal widely used in many industries due to its light weight, durability, and resistance to corrosion. In the processing of aluminum, particularly in casting and forming processes, various techniques and methods are applied to improve the properties of pure aluminum and enhance the performance of alloyed metals. These processes not only make aluminum more efficient and functional but also increase its cost-effectiveness. One of the critical stages in aluminum processing is the melting process performed during the production of aluminum billets. The melting process involves the liquefaction of aluminum and other alloying elements, and it is a crucial step that directly affects the properties of the final product [1].

In the aluminum melting process, unwanted oxidized compounds may form on or within the liquid metal. These oxidized compounds typically occur as a result of the interaction of metal oxides (Al2O3, SiO2, MgO, etc.) with high temperatures and oxygen in the melting furnace. Oxides are formed when the oxygen in the furnace environment reacts with the alloying elements, creating these compounds, which tend to accumulate as layers either on the surface or inside the liquid metal [2,3]. Since the densities of the oxides are different from that of molten aluminum, during the movement of the molten metal, the oxidized compounds may settle at the top or bottom of the aluminum. Additionally, the layered structures of these oxidized compounds may cause air pockets to form between the layers [4].

Refining processes are applied to purify aluminum and remove oxidized compounds. The refining process is particularly effective in separating oxides from the molten aluminum. This process typically involves the use of flux, which is injected into the molten metal with nitrogen or argon gas. The flux helps transport the oxidized compounds to the surface of the liquid aluminum, allowing the oxides to accumulate there [5,6]. Nitrogen gas reacts with the flux to facilitate the movement of oxides to the surface. This process typically occurs at temperatures above 720 °C [7,8]. As a result, this refining process ensures that the aluminum has a more homogeneous and cleaner structure.

II. MATERIAL AND METHODS

2.1. Billet Casting Process

In this study, regenerative reverberatory type furnaces were used for the alloying process of the AA6060 billets to ensure high efficiency and controlled heating. These furnaces utilize the recovery of hot gases within the furnace, providing lower energy consumption and a more homogeneous heating process [9].

In the production process, a direct-chill (DC) casting method was used. The DC casting method is a technique that ensures the rapid solidification of the liquid metal. In this method, the liquid aluminum is directly cooled with water to solidify, resulting in a vertical solidification process [10]. This rapid cooling process reduces the crystal structures in the alloy and helps form a more uniform internal structure [11]. Billets produced using the DC casting method exhibit low porosity, high density, and a homogeneous microstructure, leading to improved mechanical properties [12]. Furthermore, this method enhances the chemical homogeneity of the alloy and significantly improves the quality of the final product, enabling the production of flawless alloys [13].

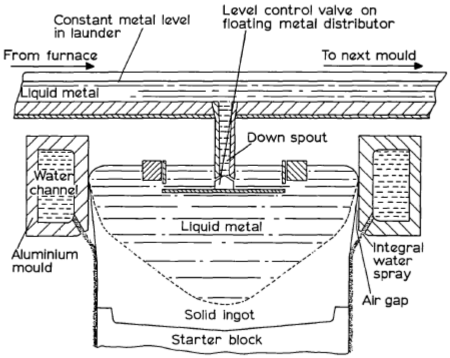


Fig 1. Schematic diagram of commonly applied vertical (DC) casting [14]

The direct-chill (DC) casting method holds a significant position, especially in billet production and the processing of commercial aluminum alloys, due to its ability to provide high efficiency and quality. This method is the preferred technique for producing large quantities of aluminum billets and plays a critical role in ensuring alloy quality and homogeneity while enhancing efficiency in industrial production [15].

The chemical analysis results for the four different castings are presented in Table 1.

Table 1. Chemical analyses of the castings

Cast No	Si %	Fe %	Cu %	Mn %	Mg %	Cr %	Zn %
Cast-1	0.48	0.22	0.02	0.03	0.49	0.01	0.01
Cast-2	0.44	0.20	0.02	0.04	0.49	0.01	0.01
Cast-3	0.45	0,23	0.03	0.06	0.48	0.02	0.03
Cast-4	0.46	0.21	0.04	0.03	0.51	0.01	0.04

2.2. Liquid Metal Quality Measurement

The quality of the liquid metal is the most important parameter affecting the quality of the cast product. A comprehensive cleaning process is essential to improve the quality of the liquid metal. This process must be carried out with optimized parameters. To summarize the melting process, raw materials are loaded into the furnace and melted within a specific temperature range. After the melting process, alloying with metallic materials is performed, followed by the chemical composition verification stage. Once the chemical composition is confirmed, nitrogen and flux are added to remove the oxides from the metal. At this stage, the flow rate of the nitrogen gas is of great importance. If the nitrogen flow rate is kept too low, the oxides will not be sufficiently brought to the surface, leading to undesirable changes in the quality of the liquid metal. On the other hand, if the nitrogen flow rate is excessively high, nitrogen may react with the oxidized compounds, incorporating them into the liquid metal and causing contamination of the metal [16].

The RPT Device solidifies at a reduced pressure of 80-100 mbar. The density index is determined by the density measurement method. Samples are weighed both in air and water. The density of the sample, ρ, is given by the following equation; where W_a and W_w are the weights of the sample measured in air and water, respectively, and ρ_{air} and ρ_{vacuum} represent the densities of the sample solidified under air conditions and under vacuum in the RPT device, respectively.

$$\rho = W_a / W_w$$

$$\rho_{index} = 100\ x \frac{\rho_{air} - \rho_{vacuum}}{\rho_{air}}$$

When the casting process reaches its stage, the quality of the liquid metal is typically monitored using the Reduced Pressure Solidification (RPT) method, and a sample is taken during this process. The RPT technique involves solidifying the liquid metal in a vacuum environment while simultaneously taking a sample under atmospheric conditions. The two samples taken in this method, one solidified in the air atmosphere and the other under vacuum, are cooled under different conditions. After the cooling process, the density index (DI%) of both samples are obtained by performing density calculations. Since the density index may not always provide sufficient reliability, the samples are then cut and polished, and the porosities formed on their surfaces are measured. This calculation method is called the BiFilm index (BI). Dispinar and Campbell introduced a method for calculating the inclusions and hydrogen level by digitally examining the cross-section of the RPT sample and measuring the voids on the surface [17,18]. They suggested measuring the maximum length of the pores as an indicator of BiFilm length and introduced a new metric called the BiFilm index (BI) [19,20]. Additionally, some studies can be referenced that delve deeper into the impact of these techniques on casting quality control. For example, Zhang and colleagues examined the porosity and microstructural characteristics of metals solidified under vacuum, detailing how these parameters affect the fluidity and casting quality of the liquid metal [21]. Furthermore, Wang et al. examined the relationship between the BiFilm index and the mechanical properties of castings, highlighting how porosity and inclusions affect mechanical strength [22].

BiFilm index (BI) can be calculated as follows:

$$BI = \frac{L_{max}}{L_{average}}$$

L_{max}: Observed maximum pore length.

$L_{average}$: Average length of all pores [23,24]

In this study, the effects of flux quantity and duration on the quality of the liquid metal were investigated. The quantity and duration parameters of the castings are given in Table 2.

Table 2. Flux quantity and cleaning duration parameters of the castings.

Sample Name	Nitrogen Pressure (Bar)	Flux(kg/ton)	Cleaning Time(kg/min)
Cast-1	2	2.15	6.25
Cast-2	2	2.15	4.16
Cast-3	2	1.42	4.16
Cast-4	2	1.42	2.77

2.3. Heat Treatment Process

After the billet casting is completed, microstructure and grain size analyses will be conducted. For the improvement of mechanical properties, it is necessary for the grain sizes to be homogeneous and of similar sizes, and the formation of dissolved compounds such as Mg□Si. To achieve this, one of the heat treatments, homogenizing annealing, is applied. For AA6060 alloys, homogenizing annealing was performed at 580 °C for

8 hours. Four different castings were made using the same parameters, and then microstructure examinations were conducted.The heat treatment data applied to the casting samples are presented in Figure 2. Heat treatment plays a crucial role, particularly in Al-Mg-Si alloys, in regulating the microstructure and improving mechanical properties. The homogenizing annealing of AA6060 alloys ensures the uniform distribution of the dissolved Mg_2Si phases, leading to a more consistent microstructure in subsequent processes. In this context, the homogenization process is applied to allow the dissolved phases to move from the grain boundaries inward, resulting in a more homogeneous alloy [25].

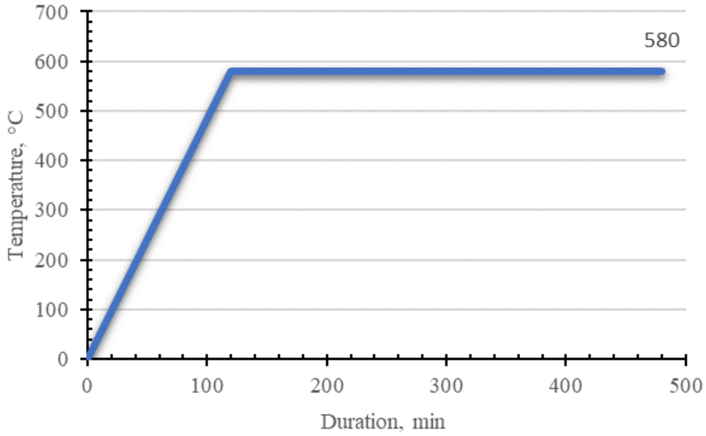


Fig. 2.Homogenization process chart of all castings

III. RESULTS AND DISCUSSION

3.1. Liquid Metal Quality

In the study, the post-filtration images of the RPT samples taken from the liquid metal, according to the casting numbers, are provided in Figure 3. After the completion of the RPT process, the samples were cut in half, and their surfaces were polished to make them smooth. These images were used for the BI examination.

Cast-1 Cast-2 Cast-3 Cast-4

Fig. 3. RPT sample images

The density index, hydrogen level, and BI obtained from the RPT samples are provided below. In Figure 4, the density index before and after filtration are presented for comparison.

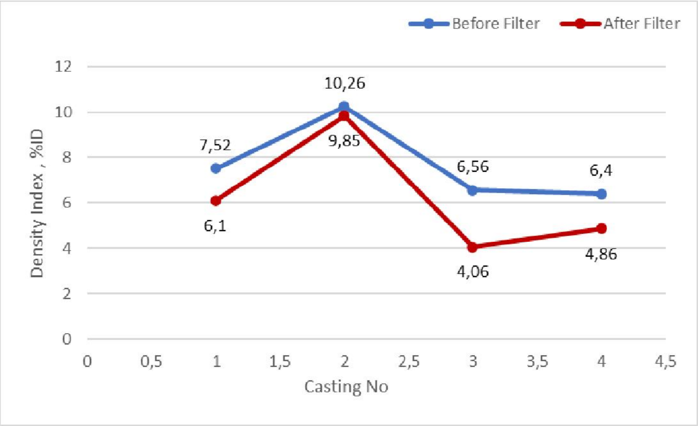


Fig. 4. Density index of the samples

In Figure 5, the BI of the samples before and after filtration are presented for comparison.

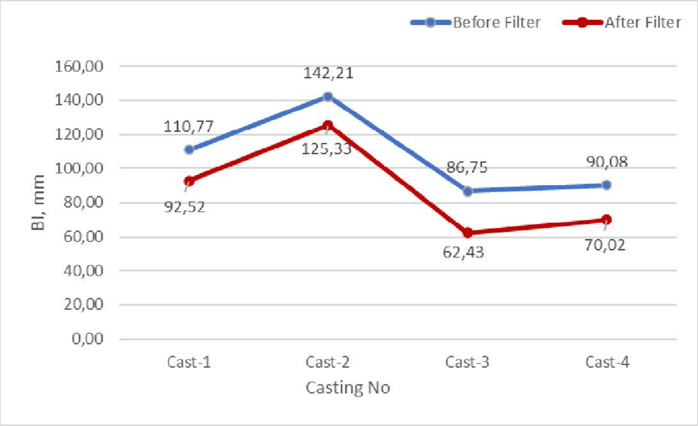


Fig. 5. BiFilm indices of the samples

In Figure 6, the hydrogen levels of the samples before and after filtration are presented for comparison.

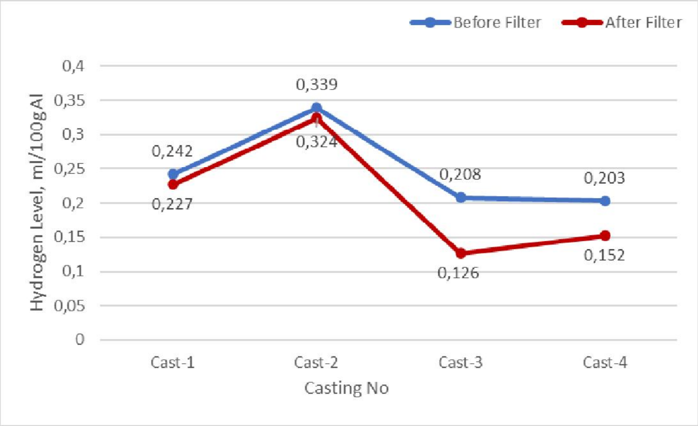


Fig. 6. Hydrogen levels of the samples

3.2. Microstructure Analysis

Based on the microstructure examinations, images of samples taken from the final stages of four different castings produced using different flux quantities and cleaning durations are presented in Figures 7, 8, 9, and 10. These images are arranged in such a way as to allow the identification of characteristics specific to each parameter, enabling a detailed examination of the microstructural properties of the samples. The analyses clearly demonstrate the effects of different production parameters on the microstructure. HF and Barker solutions were used as etching solutions in the microstructure examinations.

The microstructure examination of Cast-1 is presented in Figure 7. In this casting, the average grain size is determined to be 131 µm, and the homogeneity ratio is 78%.

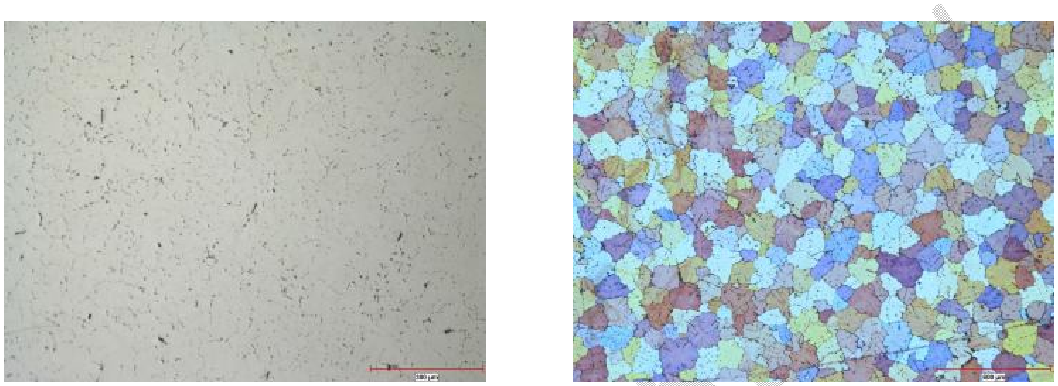

(a) (b)

Fig. 7. a) Etching with 2% HF – Central microstructure b) Barker etching – Cast-1

The microstructure examination of Cast-2 is presented in Figure 8. In this casting, the average grain size is determined to be 129 µm, and the homogeneity ratio is 70%.

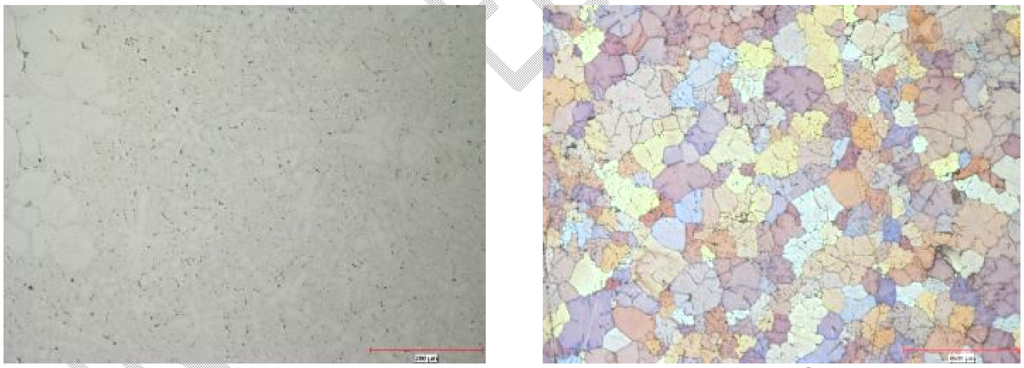
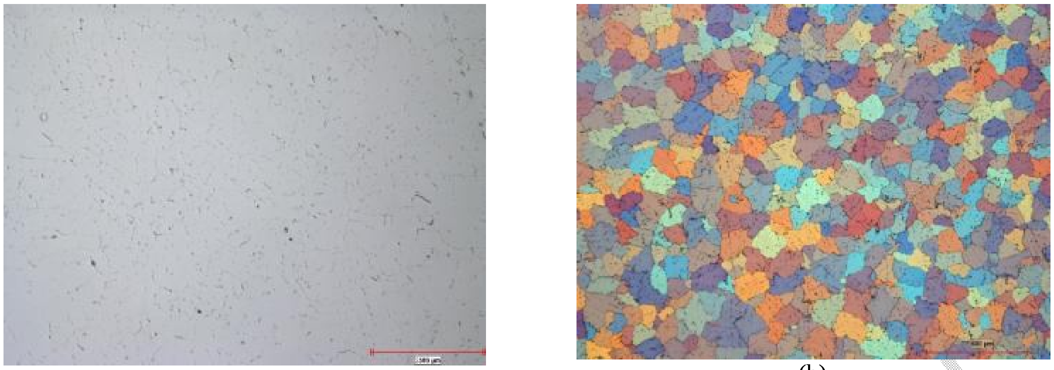

(a) (b)

Fig. 8. a) Etching with 2% HF – Central microstructure b) Barker etching – Cast-2

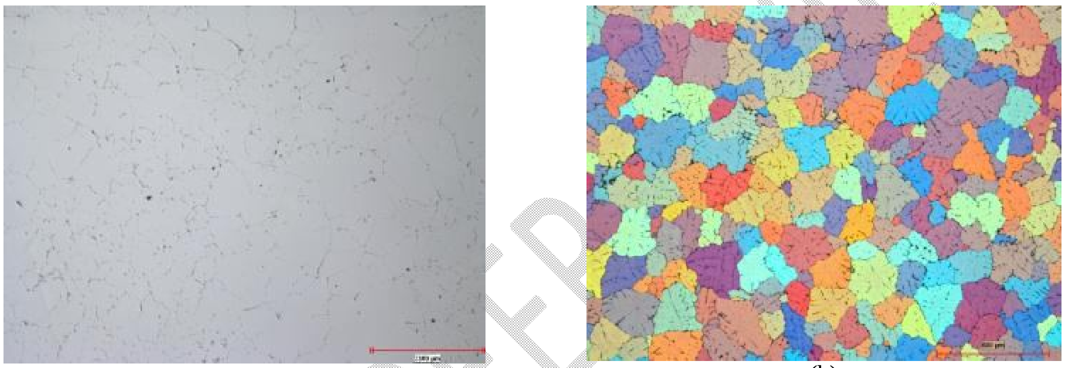
The microstructure examination of Cast-3 is presented in Figure 9. In this casting, the average grain size is determined to be 102 µm, and the homogeneity ratio is 85%.



(a) (b)

Fig. 9. a) Etching with 2% HF – Central microstructure b) Barker etching – Cast-3

The microstructure examination of Cast-4 is presented in Figure 10. In this casting, the average grain size is determined to be 164 µm, and the homogeneity ratio is 76%.



(a) (b)

Fig. 10. a) Etching with 2% HF – Central microstructure b) Barker etching – Cast-4

IV. CONCLUSION

In the conducted study, the RPT results were analyzed, and the following conclusions were drawn:

- Density Index: In the measurements taken after filtration, the highest liquid metal quality was observed in Casting 3, with a decrease of 4.06% from 9.85.
- Bifilm Index: After filtration, a decrease from 125.33 mm to 62.43 mm was observed in the Cast 3 sample. In this context, a reduction of approximately 50% in the BI was noted.
- Hydrogen Level: Upon examination after filtration, it was observed that the hydrogen level in the Cast 3 sample decreased from 0.324 to 0.126 ml/100g Al.
- Microstructure Analyses: When examining the grain sizes and homogeneity ratios, the samples showed minimal variation in their grain sizes. Upon examining the impurity levels, the best results were again obtained from the Cast 3 sample.
- Best Liquid Metal Quality: As a result of the examinations, the best liquid metal quality was achieved in the casting with a flux amount of 1.42 kg/ton and a flux and gas removal time of 4.16 kg/min.

Key Takeaways: The study highlights that both the amount of flux used and the gas removal time are crucial factors for enhancing liquid metal quality. Cast 3 exhibited the highest quality across all parameters, making it the optimal sample in this study. The results of the RPT measurements conducted yielded the following key findings.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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