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Design and manufacturing of reduced pressure test machine for determination of liquid aluminum quality in casting

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ABSTRACT

Secondary aluminum derived from discarded aluminum and its alloy products is referred to as scrap. The use of secondary aluminum is significant due to reducing the raw material costs, conserving the energy and being beneficial to the environment. It's critical to ensure the quality of the liquid metal when utilizing secondary aluminum. To produce higher quality parts, the liquid aluminum must be free from undesirable substances. The liquid aluminum is cleaned by myriad techniques depending on the capacity and conditions of the foundry, and its cleanliness is controlled by different test methods. This study involved the design and manufacturing of the most commonly used vacuum solidification device to assess the liquid metal quality after cleaning scrap aluminum alloys. The device's effectiveness was evaluated through post-production assembly and experimental studies, which yielded positive results in determining the liquid metal quality.

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1. INTRODUCTION

Aluminum casting alloys are essential engineering materials thanks to their many advantageous properties, such as high strength-to-weight ratio, high electrical and thermal conductivity, and good corrosion resistance. For this reason, its use is expanding and is used in different sectors [1]. There are two ways to supply the raw materials for aluminum production: i) refining ore (primary ingot), and ii) recycling scrap (secondary ingot). The primary ingot is produced by processing the bauxite ore, which is found in raw form in nature [2]. Compared to recycling from scrap, primary ingot production requires higher energy [3]. Aluminum's recyclability, energy consumption, cost, and positive environmental effects increase the importance of secondary aluminum. The main challenge in using recycled aluminum is ensuring high-quality liquid metal and needing extra processes when melting and casting scrap [2-6].

In the production of aluminum alloy casting parts, the presence of Fe-containing intermetallic phases, biofilms such as dissolved hydrogen, and inclusions can hurt the quality of the liquid metal. Poor liquid metal quality can result in the casting parts being rejected as scrap, as well as affect the melt's fluidity, cause the formation of micropores and cracks in the casting, reduce machinability, and hurt the mechanical properties of the casting [5-8]. For these reasons, it is necessary to increase liquid metal quality to produce higher-quality products from secondary aluminum. Hence, ongoing research is being conducted to carry out various liquid metal cleaning processes, ranging from the utilization of inert gas to tablets [2]. There are many methods for cleaning liquid metal, such as flux usage and degassing techniques including rotary type, electromagnetic, ultrasonic, and vacuum [9-12].

Various test methods are also available to check the suitability of liquid metal cleaning processes. Some of the tests used are solidification under vacuum, K-mold, thermal analysis, X-ray, Tatur test, ultrasonic test, PoDFA, Qualiflash disk, and electrical resistance method [9-17]. The reduced pressure test technique is the most widely used among these test methods because of its low investment cost, high production rate, and application practicality. The test works by cooling molten aluminum in a vacuum, leading to gas pores forming. The pressure is reduced to 80 mbar during the test. The sample is poured into a steel crucible with a liquid metal capacity of approximately 200 g and held until it solidifies. To compare the samples, they are visually inspected by cutting them in half, using density measurements, or through various image analysis programs after metallographic preparation. A lower number of pores means a cleaner melt [18-20].

The porosity observed in the reduced pressure test (RPT) samples depends on two factors: i) dissolved gas content and ii) inclusion content. This is because gas pores in aluminum castings almost always form on oxide films [20]. Brondyke and Hess were the first to demonstrate the effect of inclusion content on the RPT result. RPT samples were taken before and after an in-line filter by them. The filtered metal was denser and had significantly

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reduced porosity. Therefore, the RPT test evaluates the metal's inclusion and gas content [21].

In this study, a reduced pressure test machine was designed and manufactured to control the effectiveness of the cleaning processes applied in casting aluminum alloys. When melting secondary aluminum alloys, samples were taken with the device before and after the liquid metal cleaning process. The efficiency of the metal treatment was evaluated by measuring the density of the cast samples and examining the cross-sectional surfaces.

2. RPT MACHINE DESIGN

In this study, a vacuum solidification device was designed and manufactured. The design was created using the CAD package program. The vacuum chamber is on the right, and the pump is on the left to enhance usability. Figure 1 shows the 3D solid model image of the device with its parts. Additionally, Figure 2 shows the technical drawing of the device design with dimensions of 325x650x350 in mm.

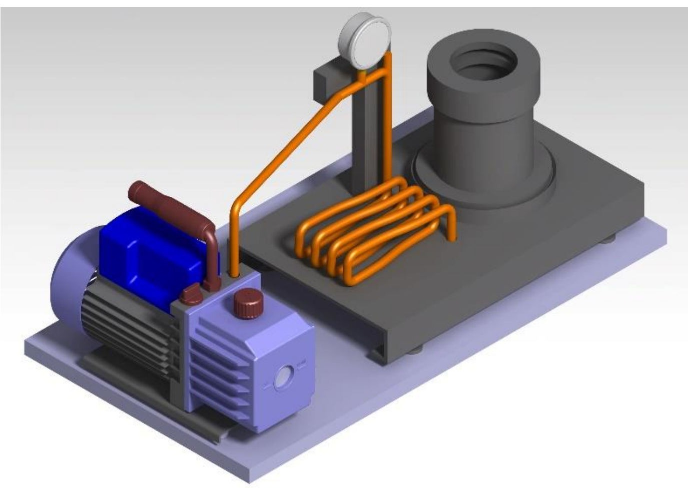


Fig. 1. Three-dimensional design view of the RPT machine.

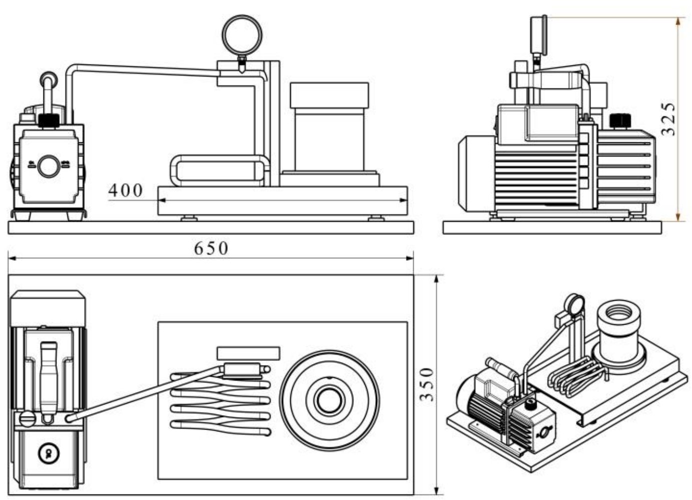


Fig. 2. Technical drawing of RPT machine.

In the design stage, the care was taken to use standard parts produced commercially, economically, and practically in manufacturing the device.

3. MANUFACTURING OF DESIGNED RPT MACHINE

The necessary materials such as sheet metal, copper pipes, solid shafts, glass, and plexi plate parts were acquired and processed during the manufacturing process based on the design specifications. Additionally, the feet, o-ring seal, vacuum manometer, vacuum pump, and pneumatic fittings were directly supplied and used in the assembly process. The manufacture of the device started with the construction of the vacuum chamber, which can be seen in Figure 3. The chamber consists of various parts, including a base, a cup, sealing gaskets, glass, plexiglass, and a cover arranged from bottom to top. The base was machined from a full spindle on a lathe to the desired dimensions outlined in the design. A hole was drilled in the base part according to the connecting elements and threaded with a guide to ensure the vacuum line was adequately connected to the vacuum chamber. In the production of the cup part, first, the flange is welded on both sides of the thick tube, and then the piece obtained in raw dimensions is machined on a lathe. This part is also threaded on the lathe to attach the cover part. Afterward, channels were opened on both sides to attach the sealing gasket to the part. The cover part is brought to the appropriate form by the internal diameter turning from the solid shaft and then threaded to be combined with the cup. After the manufactured parts were painted, the sealing gaskets were installed. The glass and the plexiglas were used to observe the solidification of the cast sample. These parts are positioned between the lid and the mug. The lid is connected to the cup part by screwing; thus, the vacuum chamber is ready. The visuals of the parts that make up the vacuum chamber are given in Figure 3.

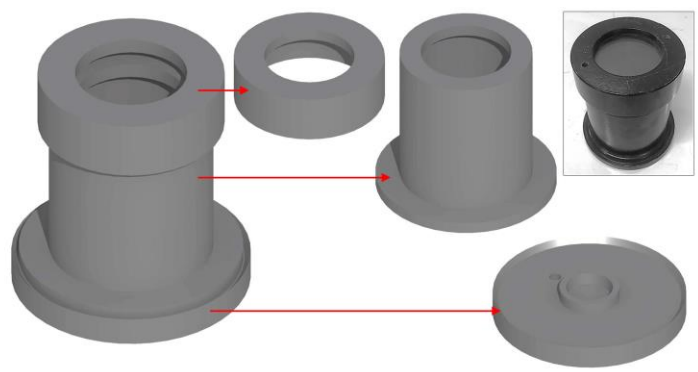
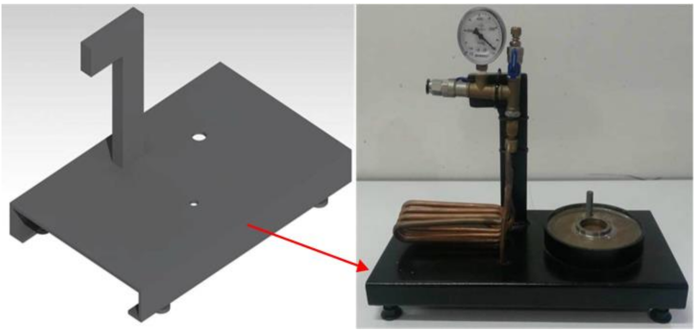


Fig. 3. Vacuum chamber components and fabrication.

The parts of the device, except for the vacuum pump, are fixed to the body. The body is made of sheet metal and profile materials. The lower part of the body is in a C shape because the sheet metal plates are bent according to the design. As seen in Figure 4, the L-shaped part of the profile was joined on the base by gas metal arc welding to mount the pneumatic connection elements and vacuum gauge on the body. Holes are drilled in the drill stand for the vacuum chamber and foot connections. After sanding and cleaning, the body is painted black. To ensure the body stands properly, four wedges are used. Figure 4 shows the completed body.



(a) (b)

Fig. 4. Body design (a) and manufacturing (b).

A copper pipe, pneumatic connectors, a vacuum gauge, and a plastic pipe were used to create the vacuum line of the device. The line started with the copper pipe from the vacuum chamber, as it provides rapid heat transfer and resistance during solidification. During solidification, some liquid metal heat is carried over the vacuum line along with the evacuated air. For this reason, copper pipe was preferred, considering the rapid heat transfer and heat resistance. The cooling section is formed by coiling the copper pipes spirally. At the end of the cooling section, the pneumatic connection elements are connected to the line. In addition, the vacuum gauge is attached to these fasteners, and the vacuum pressure, an essential solidification parameter, is adjusted. The connection between the vacuum chamber and the vacuum pump is established by fixing a plastic pneumatic hose at the end of the vacuum line. The assembled and ready-to-use visuals of all parts of the device are given in Figure 5.

Fig. 5. Ready-to-use reduced pressure test machine.

4. EXPERIMENTAL STUDIES AND VERIFICATION TESTS

The equipment manufactured for this project works by pouring the liquid metal sample into the steel crucible, placing the sample in the vacuum chamber, and solidifying it under vacuum. Before use, the device underwent a leak test by monitoring the vacuum pressure over time. The pressure remained constant, indicating no leaks. Afterward, tests were carried out with aluminum liquid metal. After the scrap aluminum alloys were melted, samples were taken before and after cleaning with nitrogen. Thus, the metal was tested in the solidification device under vacuum, and the suitability of cleaning procedures was checked. After solidification, density tests and cross-sectional surface examinations were conducted on the samples.

Density measurements of the obtained samples were carried out according to the Archimedes principle. According to this principle, the weights of each sample were weighed first in air and then in pure water, the density of which was d_w=0.998 g/cm^3. The weighing process was carried out with the Archimedean mechanism installed on the electronic balance with a sensitivity of 0.02 g, shown in Figure 6.

Fig. 6. Density measuring setup.

The density measurements of the samples were calculated by using the formula in Equation 1. Here, d_e is the density of the cast sample, m_a is the weight of the sample in air, m_w is the weight of the sample in pure water, and d_w is the density of water at room temperature. The % porosity values of the samples were calculated with the formula in Equation 2. Here, d_t is the theoretical density of the sample, and d_e is the experimental density of the casting sample calculated in Equation 1.

$$d_e = \frac{m_a}{m_a - m_w} \times d_w \tag{1}$$

$$\%\, porosity = \frac{d_t - d_e}{d_t} \times 100 \tag{2}$$

In addition, the sample was cut in half vertically, and the surfaces were subjected to grinding. The images were obtained with the help of a scanner to see the porosity on the sample cross-sectional surfaces.

In Figure 7, all the surface depression images of the samples obtained in the device before and after the liquid metal cleaning of the scrap aluminum alloy are given.

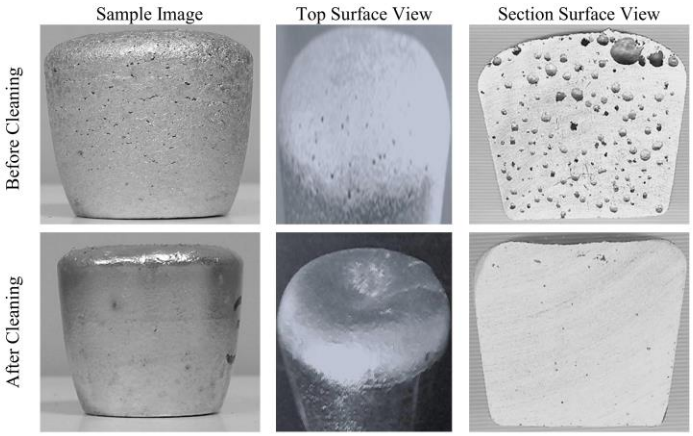


Fig. 7. The sample image, top surface, and section surface view images of the samples.

The part surfaces shown in Figure 7 is swollen since the amount of gas is high in the samples obtained without liquid metal cleaning. Nevertheless, upon undergoing liquid metal cleaning, the upper part of the sample displays shrinkage. This is known as an indication that liquid metal cleaning is appropriate. The distribution of porosity on the cross-sectional surface is a clear indicator of liquid metal cleaning clearly. While all sides have porosity in the sample obtained before cleaning, it is understood that an acceptable level of liquid metal cleanliness has been reached in the cast sample after cleaning. This is evident from the surface depression and the reduction in the porosity levels. The device used for the test shows appropriate results after the cleaning process. Density measurements were done, and Table 1 presents the calculated porosity values in %.

Table 1. Density and porosity results of samples.

Sample Type	*Weight in air (g)*	*Weight in water (g)*	*Experimental density (g/cm^3)*	*Theoretical density (g/cm^3)*	*Porosity (%)*
Before cleaning	110.12	65.78	2.48	2.67	7.15
After cleaning	112.34	70.18	2.66	2.67	0.38

Table 1 shows the density measurement results based on porosity value calculations of both experimental and theoretical density. To determine the theoretical density value, the chemical composition of the alloy and its standard values were taken into account. Before cleaning, the porosity value was 7.15%, but it was observed that the relevant value was 0.38% after cleaning. This indicates that the liquid metal quality is convenient, and the device can accurately detect the test results, as the obtained value is below the 0.5% threshold.

5. CONCLUSIONS

In this study, the design and manufacturing of the solidification device under vacuum was carried out. Aluminum casting samples were used, and trial tests were performed. The results are presented below:

- A reduced pressure test evaluation of metal quality was made by providing the necessary vacuum pressure with the device.
- It has been determined that the liquid metal cleanliness control in casting of aluminum alloys can be done with the relevant test device.
- It has been observed that the porosity values are quite high when the cleaning process is not performed when casting secondary aluminum.
- When the liquid metal cleaning process is performed, it has been determined that there will be a minimum level of porosity in the casting after the liquid metal is cleaned.

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