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MOLD DESIGN FOR INJECTION MOLDING MACHINE USING RECYCLED ALUMINUM

1) Mechanical Engineering Department, Politeknik Negeri Bali

Correponding email [1] :
nurinbaiti@pnb.ac.id

Amadeus Renaldy [1], Risa Nurin Baiti [1]*, I Putu Gede Sopan Rahtika [1], Komang Widhi Widantha [1]

Abstract. The use of aluminum is widely spread from beverage cans, car parts, airplanes, trains, and household furniture. This is due to its lightweight and good corrosion resistance. However, as a metal aluminum waste is difficult to be decomposed naturally. Aluminum metal takes 80 to 100 years to decompose. So the accumulation of untreated scrap aluminum can pollute the environment. One of the solutions is to recycle aluminum by melting and re-casting it into a new shape: a mold for polymer processing. The waste of beverage cans was cleaned from any dirt and adhesive. Then, they were turned into small parts by a crusher. The melting process was done at 650°C. The molten aluminum was poured into a sand mould in the shape of mould of a tensile testing specimen. The recycled product can be used to prepare tensile testing samples of polymer or polymer-based composite with injection molding technique. To evaluate the quality of recycled aluminum, a hardness test was done with a value of 69.31 $\pm$ 3.02 HB. This value is lower than first-use aluminum. This is due to a combination of microstructural changes due to repeated heating, the presence of additives and impurities, and the effects of heat treatment and open cooling. Metallographic testing was carried out to evaluate the microstructure of the material resulting from the smelting of scrap aluminum using sand molds. In this test, the etching solution used consisted of 100 ml of water and 20 g of sodium hydroxide. The results of the metallographic images on the recycled aluminum material show the presence of a stand-alone silicon (Si) element and an aluminum-copper alloy ($CuAl_2$).

Keywords : aluminum, mould, injection molding, design, and recycling.

1. INTRODUCTION

The use of aluminum as a base material continues to increase due to its widespread availability and diverse applications in industries such as automotive, aerospace, railways, and household furniture (Sinaga, 2016). This increase has led to an increase in the amount of aluminum waste that is no longer used, such as alloy wheels, household appliances, soft drink cans, and engine blocks. As a result, new problems with the accumulation of aluminum waste have emerged (Fasya & Iskandar, 2015). Aluminum waste is solid waste and is difficult for the environment to decompose. Aluminum metal takes 80 to 100 years to decompose (Prakoso et al., 2019), so the accumulation of untreated scrap aluminum can pollute the environment. This happens because metals take a long time to dissolve in water and decompose in the soil (Fasya & Iskandar, 2015). Pollutants can come from waste that has been buried for a long time without being processed. The rain will wet the garbage pile, and will make the situation worse (Bagus, 2002). On the other hand, the production of aseptic packaging in Indonesia reaches 4 billion items per year, or around 333 million items per month, which makes it one of the largest contributors to waste. Most people burn aseptic packaging waste to dispose of it, but this method is considered ineffective because aluminum foil and CO2 gas left behind pollute the air and pollute the environment (Anggreani et al., 2017). If no effort is made to overcome environmental pollution caused by waste, this problem will become worse over time (Bagus, 2002).

Recycling is the best way to eliminate aluminum waste (Anggreani et al., 2017). Aluminum can be recycled through the casting process (Fasya & Iskandar, 2015). One of the most commonly used types of aluminum casting is by sand casting technique. Sand casting has the advantages of low production costs, reusable, heat resistance, easy operation, and good casting product results. Sand casting method is environmentally friendly and efficient for industrial practices. The sand casting process requires special attention to several key aspects to ensure optimal results. The channel system, as shown in the first study, has a vital role in facilitating the flow of molten metal into the sand mold. Various channel models, such as split channels, split channels with additives, and direct channels, affect tensile strength and possible shrinkage defects in cast results (Hendaryati & Mamungkas, 2021). Furthermore, the second study highlights the importance of sand mold variations in recycled aluminum casting. Variations such as red sand mold, dumpling sand mold, and mixed sand mold affect the percentage of shrinkage and hardness of cast products (Mulyanto, 2018). Another significant aspect in the casting process is the selection of molding materials, where the use of RCS (Resin Coated Sand) waste as a substitute for silica sand can provide positive benefits to the environment and the economy. Overall, a deep understanding of the channel system, mold variation, and mold material selection are key to improving quality and efficiency in the sand casting process (Sanusi et al., 2023).

In addition to its high recyclability, which significantly reduces the carbon footprint, aluminum also has the mechanical strength and durability required for the injection molding process (Hendaryati & Mamungkas, 2021). The integration of sand casting in aluminum recycling not only minimizes environmental impact but also enhances efficiency in industrial production. Utilizing recycled aluminum in the manufacturing of injection molding molds presents a significant opportunity to improve sustainability while simultaneously reducing waste. This research aims to promote the application of recycled aluminum in support of plastic recycling efforts, thereby addressing both environmental and industrial challenges through a sustainable and innovative approach.

2. METHODS

Figure 1 shows the intended final shape of recycled aluminum, which is the mold for injection moulding equipment. Usually, the mold for injection molding technic is made out from metal block. Then, it is shaped by machining process such as frais and bor that results in many unused metal chips.

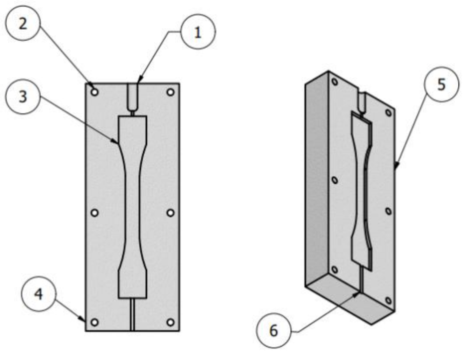
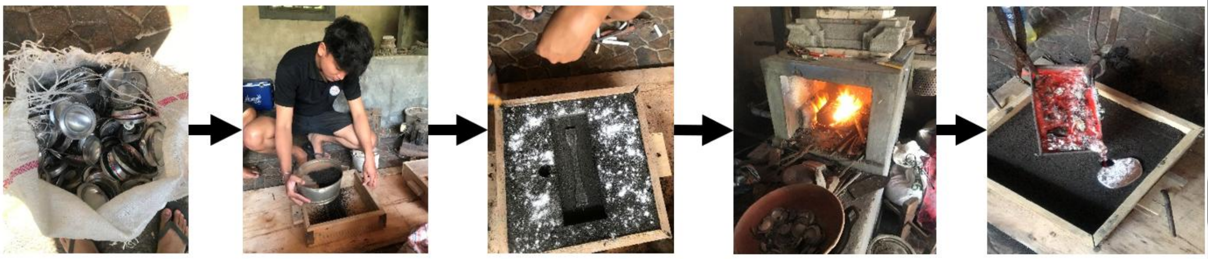


Figure 1. Designed shape of recycled aluminum

Image Legend:
1. Nozzle
2. Bolts
3. ASTM D638 tensile test sample specimen mold
4. Bottom mold
5. Top mold
6. Vent



Aluminum scrap → Prepare sand mould → Sand mould → Melting process → Pouring

Figure 2. Aluminum recycling process

The process of aluminum recycling process is shown in Figure 2. The sand mold was prepared using uniformly sized silica sand mixed with a bentonite binder to improve cohesion and mold integrity. The sand mixture was then compacted to ensure uniform density and reduce defects in the final cast product. The melting process was done in a crucible pot at 650ºC. To improve the quality of the molten aluminum, flux was added to remove oxides and other impurities, and a degassing process was performed to eliminate trapped gases, reducing porosity in the final cast. The purified molten metal was then carefully poured into the cavity of the sand mold. The bottom and top molds were separately prepared in dedicated sand molds to facilitate assembly.

The mechanical properties of the recycled aluminum were evaluated through Brinell Hardness testing and metallography, both conducted at the Material Testing Laboratory, Bali State Polytechnic. The Brinell Hardness test was performed using a 10 mm diameter hardened steel ball indenter under a 500 kgf load, following ASTM E10 standards. Each test was conducted for 10 to 15 seconds to allow proper indentation. The diameter of the indentation left by the steel ball was measured using a precision microscope, and the Brinell Hardness Number (BHN) was calculated. Multiple readings were taken at different locations on the sample to ensure accuracy and uniformity in hardness distribution. Metallography testing was carried out to analyze the microstructure of the cast aluminum and identify key structural characteristics such as dendritic formations, grain boundaries, and porosity levels. The samples were carefully sectioned using a precision cutting machine, followed by sequential grinding with silicon carbide abrasive papers (ranging from 240 to 2000 grit) and polishing with alumina suspension to achieve a mirror-like surface. Observations were made using an optical metallurgical microscope at magnifications ranging from 100x to 500x, enabling a detailed examination of grain structure, defects, and phase distribution.

The final stage involved evaluating the functionality and efficiency of the recycled aluminum mold in an injection molding machine. The mold was securely installed in the machine, and HDPE (*High-Density Polyethylene*) plastic was used as the test material. Key parameters, including mold filling behavior, cooling efficiency, and ejection performance, were monitored throughout the process. After molding, the plastic specimens were inspected for defects such as warping, incomplete filling, sink marks, and surface roughness. Dimensional accuracy was assessed using a digital caliper, while visual inspection under proper lighting conditions helped identify surface imperfections. The results were analyzed to determine the effectiveness of the recycled aluminum mold in producing high-quality plastic components, ensuring its suitability for injection molding applications.

3. RESULTS AND DISCUSSION

3.1 Sand Casting

Sand Casting requires sand as a printing medium, and the quality of sand greatly affects the quality of the products produced. Mountain sand, beach sand, river sand, and silica sand are the most commonly used types of printed sand [5]. Molding sand should have the following properties: formable, permeable, large grain distribution, resistance to the temperature of the metal being poured, proper composition, durable, and inexpensive [6]. The selection of the main materials in the form of river sand and bentonite is based on the characteristics of each material that suits the needs of the metal casting process using sand molds. River sand was chosen because it is easy to obtain, has a uniform grain size, and has a relatively low cost. Experimental grain size analysis revealed an average particle size of 200 µm, indicating a suitable balance between permeability and strength. In addition, river sand has good refractory properties, being able to withstand high temperatures without experiencing significant deformation. Bentonite, a type of clay with high binding ability, was chosen to be mixed with river sand. The binding properties of bentonite help in improving the strength and stability of sand molds. Many studies have shown that bentonite, the most commonly used binder material, is an ideal binder for sand molds. However, the price of bentonite is quite expensive in the market when compared to other types of binders. The CaO (clay) content in bentonite is higher than in coal burning waste ash [7].

The selection of the 4:1 ratio between river sand and bentonite is based on several theoretical and empirical considerations. Too much bentonite in the mixture will make the mold too rigid and difficult to form, while too little bentonite will reduce the binding strength, causing the mold to be easily damaged during the casting process. By using clay or bentonite soil as a binder, cast sand exhibits a variety of different properties according to the moisture content. If the clay content is made constant and the moisture content is added, the strength gradually increases until it reaches its peak, then decreases. A similar situation occurs if the moisture content is made constant and the clay content is added. As the excess water clay fills the space between the grains of sand, its strength and permeability will decrease [7]. The 4:1 ratio is considered ideal because it provides the right balance between flexibility and mold strength. This composition results in a mold that is strong enough to withstand the pressure of molten metal and flexible enough to disassemble without damaging the shape of the mold.

The metal raw materials, the type of furnace used, and the amount of material to be melted must be appropriate [8]. The aluminum smelting process is carried out using a melting furnace assisted by *Blower* to ensure strong and constant airflow, improve the efficiency of burning coconut charcoal as fuel. Coconut charcoal was chosen because of its abundant availability and ability to produce high temperatures sufficient to melt aluminum. *Blower* used to maintain the required high temperature during the smelting process, ensuring that the aluminum melts perfectly before being poured into the sand mold.

3.2 Hardness Test

The test results showed that the average hardness of the material was 69.31 HB±3.02. This value reflects the consistency and homogeneity of the material quite well, which indicates that the smelting and casting process has been carried out correctly. This test was carried out with 10 data retrievals.

Table 1. Comparison of aluminum hardness

No.	Cast Raw Materials	Average Hardness (HB)	Reference
1.	Pure Aluminum	101.26 HB	[1] (Widodo & Subardi, 2019)
2.	Aluminum Cans	124.44 HB	[2] (Dwi Putra et al., 2023)
3.	Used Motorcycle Wheels + Si	42 HB	[3] (Hidayanto et al., 2018)
4.	Aluminum Cans	69,31 HB	(Renaldy, 2024)

The use of aluminum recycled materials can lead to a decrease in mechanical properties, in particular its hardness value (see Table 1). This is due to several factors related to the repeated forming and heating process experienced by recycled aluminum, as well as a decrease in its purity level due to the mixing of additives and impurities because during the smelting process, the quality of aluminum should not be mixed with dirt or other foreign objects which can reduce the quality of the melted aluminum to get good casting results [8]. Recycled aluminum has often undergone various previous heating and forming processes, which can lead to changes in the material's microstructure, such as excessive grain growth or the formation of unwanted phases. And the material becomes softer due to the larger grain limit due to the longer cooling time (Prativi & Parmitha, 2013). Excessive grain growth reduces the hardness of the material because larger grains have fewer grain limits per unit volume, thus lowering the resistance to plastic deformation.

This is in line with research conducted by [3] which shows that the hardness of the cast brinnel has the highest hardness value at 670°C, with an average hardness value of 42 HB. The hardness value decreases in general as the pouring temperature increases. In the context of microstructures, this condition indicates that large microstructures have a high hardness value, while small-sized microstructures have a low hardness value [3]. In addition, if the pouring temperature is higher than 650°C, the hardness value of the casting will decrease as shown in Figure 3 [10]. And recycled aluminum usually contains additives and impurities that enter during the recycling cycle, which can lead to the formation of unwanted inclusions and phases in the aluminum microstructure, weaken the bonds between atoms, and reduce hardness and other mechanical properties.

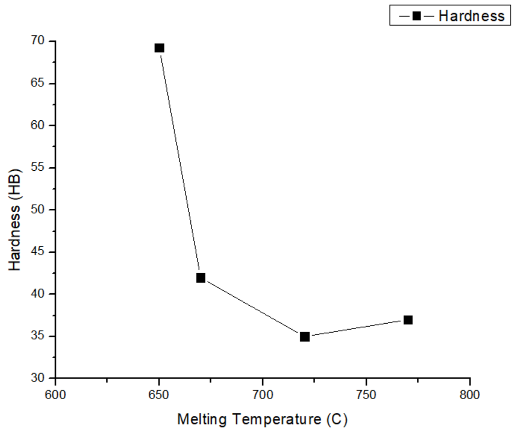


Figure 3. Effect of melting temperature in recycled aluminum hardness value.

During the finishing process, recycled materials are often subjected to additional heat treatments such as *annealing* or *normalizing*. Heating temperature, the time required to maintain the temperature (*holding time*), cooling rate, and environment are some of the variables that affect heat treatment. Heat treatment is the combination of the process of heating or cooling a metal and combining it in a solid state to achieve the desired properties. Temperature limits and cooling speeds are essential to achieve this. For example, normalization is a heat treatment process in which a heating temperature is reached and then cooled slowly using an air conditioning medium. It is the cooling process that greatly affects the mechanical properties of the material. Materials with higher strength and hardness mechanical properties if cooling is done quickly, while if cooling is done slowly, the opposite will happen.

It was concluded that the longer the specimen was subjected to normalized heat treatment, the lower the hardness value. The long heat treatment also causes changes in the microstructure of the specimen [11]. Thus, the decrease in hardness in aluminum recycled materials is due to a combination of microstructure changes due to repeated heating, decreased purity due to additives and impurities, as well as the effects of heat treatment and open cooling which leads to the formation of unwanted microstructures and thermal tension. The pouring temperature affects the microstructure and hardness of recycled Al-Si.

3.3 Metallography

In this test, the etching solution used consisted of 100 ml of water and 20 g of sodium hydroxide, in accordance with aluminum metallurgical guidelines [4]. This test is important because the microstructure of a material can determine the mechanical properties and performance of a material in a given application. The results of the metallographic images on recycled aluminum materials, shown in Figure 4, gives the presence of a stand-alone silicon (Si) element and an aluminum copper alloy ($CuAl_2$). The microstructural examination showed relatively coarse grains, indicating a slow cooling rate during solidification, which promotes grain growth and reduces hardness. The Si phase was evenly dispersed within the aluminum matrix, while $CuAl_2$ appeared along grain boundaries, contributing to strength but also increasing brittleness. Additionally, some defects such as porosity and microcracks were observed, likely caused by gas entrapment or impurities introduced during the recycling and remelting processes. These defects can negatively impact mechanical properties by reducing overall strength and fatigue resistance. The presence of these phases and structural imperfections helps explain the hardness reduction and mechanical performance of the recycled aluminum, emphasizing the effects of grain growth, impurity segregation, and casting defects.

Based on the guidelines on beverage containers 3104-H19, it is known that the compound content in the aluminum material includes Si elements of 0.61%, Fe 0.8%, and Cu in the range of 0.05%-0.25%. This microstructure reflects the original composition of the 3104-H19 aluminum beverage container material, where the presence of elements such as Si and Cu corresponds to the specifications of the alloy.

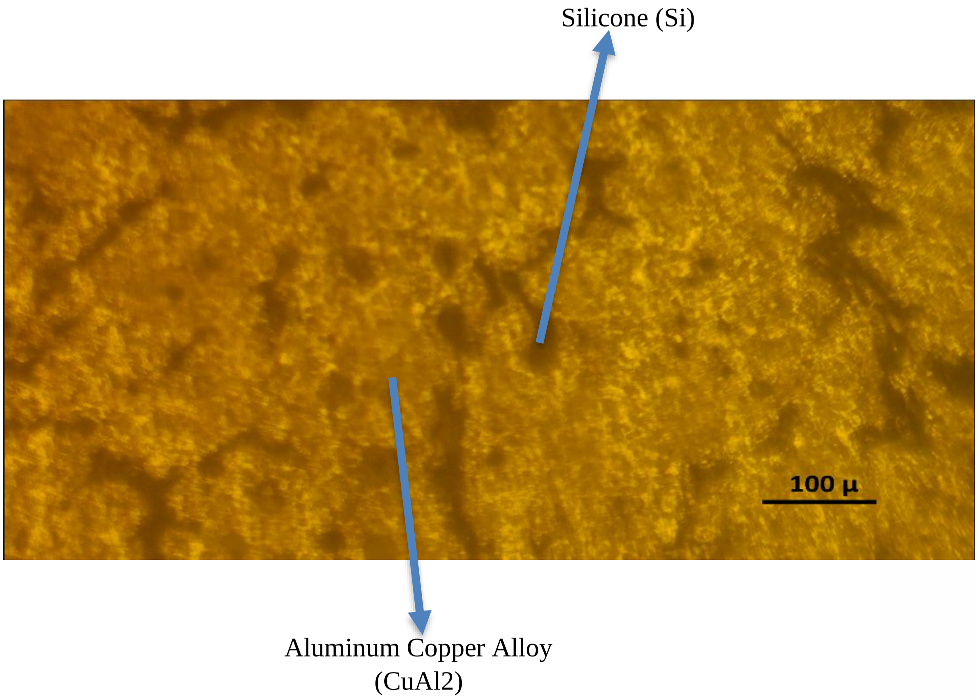


Figure 4. Microstructure of recycled aluminum

3.4 Mould testing in injection moulding equipment

The results of the HDPE (*High-Density Polyethylene*) test were carried out using *injection molding*. This test is focused on the use of melted gallon caps using *injection molding* molds that will be the form of the tensile test sample. Testing is carried out with several variations in process parameters, namely mold temperature, melting temperature, and melting time.

This test was performed with variations in mold temperature at 200^{o}C and 250^{o}C, while melting temperatures varied at 200^{o}C, 230^{o}C, and 250^{o}C. The melting time also varies, namely 3 minutes, 4 minutes, and 5 minutes. The results of these tests provide an overview of how these parameters affect the quality of the final product, such as material homogeneity, product density, and shape stability.

Figure 5. Recycled plastic product

The optimal combination of parameters was found at a mold temperature of 250°C with a melting time of 4 minutes, producing a well-formed product with a fully filled mold. However, slight defects were still present, primarily due to air or gas entrapment during the injection process and rapid cooling of the melt inside the mold. This premature cooling restricted proper flow, preventing full cavity filling and resulting in minor imperfections. To further assess product quality, the plastic specimens were examined for defects such as warping, incomplete filling, sink marks, and surface roughness. Dimensional accuracy was measured using a digital caliper, while visual inspections under proper lighting conditions helped identify surface imperfections. Warping was observed in some samples due to uneven cooling rates within the mold, causing differential shrinkage between sections. Incomplete filling was noted in certain areas where premature solidification hindered the melt from spreading evenly. Sink marks appeared on thicker sections as a result of internal shrinkage during solidification, with the outer layers cooling faster than the inner material. Surface roughness was attributed to an uneven mold surface or inadequate injection pressure. Slight variations in dimensional accuracy were detected, mainly due to mold contraction and thermal shrinkage during cooling, but most specimens remained within acceptable tolerance limits. Overall, the analysis confirmed that the recycled aluminum mold is capable of producing high-quality plastic components, making it a viable option for injection molding applications.

4. CONCLUSION

This study shows that the manufacture of injection molding molds, with dimensions of 18322.179 mm³ and using aluminum material from used beverage cans with a specific gravity of 2.7 g/cm³, has an important role in the recycling process, especially in converting aluminum waste into new products with useful value. The sand casting method used in this process has proven to be effective in aluminum recycling. The process involves melting using a melting furnace and a blower to keep the heat constant, pouring the melt at 659°C into the sand mold, dismantling the mold, and finishing by hand grinding to achieve precise results. As a result, aluminum waste is successfully converted into new products with high quality. With the right control of process variables, this technology not only reduces waste but also produces products that meet standards, playing an important role in the development of more efficient and environmentally friendly recycling.

In addition, this study aims to find out how the type of aluminum waste affects the hardness value of the product resulting from the casting process, as well as to develop injection molding as a new way to recycle aluminum. This study found that the material has a hardness value of 69.31 HB at a pouring temperature of 659°C. The microstructures formed show small dendrites, which affect the material's ability to withstand loads, so that in the end the hardness value of the material decreases. These findings make an important contribution to the development of aluminum recycling techniques and show great potential in improving the efficiency and sustainability of recycling processes.

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