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# Hardness and Microstructure Characteristics in Iron Sand Casting from Ampenan Beach with Used Canned Aluminum Alloy

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**Abstract**

**Background:** Iron sand from Ampenan Beach, Lombok, containing approximately 74.5% $Fe_3O_4$, has significant potential as a locally sourced raw material for metal casting. However, its mechanical properties, particularly hardness and microstructural uniformity, often require improvement to meet industrial application standards. One promising approach to enhance these properties is alloying with recycled aluminum materials.
**Objective:** This study aims to investigate the effect of adding recycled aluminum on the hardness and microstructural characteristics of iron sand castings.
**Methods:** The experiment was conducted using a Completely Randomized Design (CRD) with aluminum content variations of 0%, 2%, 4%, 6%, and 8%, each repeated three times. The aluminum used was sourced from recycled beverage cans with a purity of 98.7%. Hardness testing was performed using Brinell, Rockwell, and Vickers methods, while microstructural analysis was carried out using optical microscopy.
**Results:** The results indicate that aluminum addition significantly enhances material hardness. The optimum result was achieved at 6% aluminum content, resulting in a 28.8% increase in Brinell hardness compared to the control sample. Microstructural refinement was also observed, characterized by a reduction in grain size from 50.0 µm at 0% Al to 25.0 µm at 6% Al, the formation of a ferritic matrix with evenly distributed $Al_4C_3$ and $Fe_3Al$ phases, and a transformation in graphite morphology from lamellar to nodular. However, excessive aluminum addition (8%) led to a reduction in hardness due to over-alloying and phase clustering.
**Conclusion:** Optimizing the addition of recycled aluminum, particularly at a 6% composition, effectively improves the mechanical performance and microstructural quality of iron sand castings. These findings highlight the potential of recycled aluminum alloys to enhance the performance of locally sourced cast materials while supporting sustainable practices in metallurgy.

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## INTRODUCTION

Indonesia is endowed with abundant natural resources, including mineral wealth such as iron sand, which is widely distributed along coastal regions, like Ampenan Beach in West Nusa Tenggara. Rich in magnetite ($Fe_3O_4$), this sand has long been considered a potential raw material for the metal industry, particularly in the production of cast iron and steel (Mbiliyora & Hendrajaya, 2018; Soemardi & Pribadi, 2018). However, castings produced from pure iron sand often exhibit suboptimal mechanical properties, especially in terms of hardness and microstructural uniformity. This poses a challenge for the development of locally sourced materials that can meet high-performance engineering demands (Yan & Kanatzidis, 2021; Babu et al., 2019; Kim et al., 2013). Therefore, the addition of alloying elements has emerged as a promising strategy to enhance the mechanical behavior and microstructural quality of cast products (Liang et al., 2025).

Aluminum is among the most widely used alloying elements in casting, known for refining grain structure and improving hardness. Moreover, aluminum enhances tensile strength and corrosion resistance, making it particularly valuable for structural applications (Putra et al., 2025; Kim et al., 2013; Liang et al., 2025). Conventionally sourced aluminum, however, can be costly and unsustainable, prompting researchers to explore recyclable alternatives such as used aluminum cans. Using discarded aluminum cans as a secondary alloying source not only reduces production costs but also supports the principles of the circular economy and waste minimization. Incorporating recycled metals into casting processes offers a sustainable path forward for both industry and the environment (D Raabe, 2023; Sakir et al., 2020; Modolo et al., 2013).

In the context of iron sand casting using local materials, limited research exists on the effects of recycled aluminum on microstructure and hardness properties. Prior studies have either used different base metals or relied on commercial-grade aluminum, overlooking the potential of waste-derived alloying agents (Xiao et al., 2024; Soemardi & Pribadi, 2018; Sakir et al., 2020). For example, Ahmad et al. (2019) reported that the addition of aluminum improved the hardness of cast iron by up to 25%, but did not examine the role of recycled aluminum. Similarly, Ferreira Farias et al. (2019) focused more on pouring temperature and its effect on grain size, leaving the influence of alloy variation unaddressed.

This knowledge gap underscores the need for research that integrates local iron sand resources from Ampenan Beach with sustainable inputs, such as used aluminum cans, to produce high-performance, low-cost materials (Hidalgo & Verdugo, 2025; Sakir et al., 2020; Modolo et al., 2013). The novelty of this study lies in the integration of natural magnetite-rich sand from Ampenan and high-purity recycled aluminum cans. It employs a controlled experimental approach to investigate the correlation between alloy composition, microstructure morphology, and hardness a unique contribution to both local materials science and sustainable metallurgy (Sankaran & Mishra, 2017; Liang et al., 2025; Popov, 2018).

Additionally, this study employs multi-method hardness testing (Brinell, Rockwell, Vickers) and microstructural characterization using both optical and SEM- EDS microscopy, enabling a comprehensive understanding of the internal transformations resulting from alloying (Mondal, 2023; Popov, 2018; Kim et al., 2013). The urgency of this study is reinforced by growing industrial demand for cost-effective, environmentally responsible cast materials applicable to automotive, agricultural, and construction sectors. Developing alloys from waste-based sources can significantly support national sustainable development initiatives (EC, Giese, & MRS Energy, 2022; Sakir et al., 2020; Soemardi & Pribadi, 2018).

In addition to its technical contributions, this research holds significant socio-environmental value. Using discarded aluminum helps alleviate dependence on virgin materials, cuts carbon emissions, and serves as a model for green industrial practices that local enterprises could adopt (Deng et al., 2025; Sakir et al., 2020; Modolo et al., 2013).

Based on the above background, this study aims to; a) to find out the effect of the variation of used aluminum cans on the hardness of iron sand castings, b) to find out the characteristics of microstructures formed in iron sand casting results with the addition of used canned aluminum alloy, and c) to find out the relationship between the composition of aluminum alloy and changes in the microstructure and the hardness of the material hardness of the casting in Ampenan Beach, Lombok, NTB.

## METHOD

*Research Location*

This research was conducted in June and July 2025 at Ampenan Beach, Ampenan District, Mataram City, West Nusa Tenggara, Indonesia. The study focused on utilizing locally sourced iron sand from the coastal area as the primary raw material for metal casting experiments.

*Experimental Design*

The experimental design employed a Completely Randomized Design (CRD), with aluminum alloy composition as the treatment factor. Five levels of aluminum content were investigated, namely 0%, 2%, 4%, 6%, and 8%. Each treatment was repeated three times, resulting in a total of 15 experimental trials.

*Materials*

The materials used in this study included iron sand collected from Ampenan Beach, Lombok, West Nusa Tenggara, with a total mass of 10 kg, which served as the primary raw material for casting. Recycled aluminum alloy was obtained from used aluminum beverage cans with a total mass of 2 kg and utilized as the alloying element. Metallurgical coke was employed as a reduction fuel during the smelting process, while flux materials in the form of calcium oxide (CaO) and silicon dioxide ($SiO_2$) were added to facilitate slag formation. Sample preparation materials consisted of epoxy resin, sandpaper with grit sizes of 240, 400, 600, 800, 1000, and 1200, alumina polishing powders with particle sizes of 1 μm and 0.3 μm, and an etching solution prepared as 2% Nital (2 ml $HNO_3$ mixed with 98 ml ethanol).

*Equipment*

The equipment utilized in this research comprised an induction-type crucible smelting furnace with a capacity of 5 kg, which was used for melting and alloying processes. Silica sand molds with dimensions of 150 mm × 25 mm × 25 mm were employed for casting the specimens. Sample preparation was carried out using a cutting machine, mounting press, grinding machine, and polishing machine. Measurement instruments included a digital scale with an accuracy of 0.1 g and a K-type thermocouple for temperature monitoring. Hardness testing was performed using a Universal Hardness Tester Brinell HB-3000. Microstructural characterization was conducted using an Olympus BX51M optical microscope and a Zeiss EVO MA 10 scanning electron microscope equipped with energy-dispersive spectroscopy (SEM-EDS). Chemical composition analysis was carried out using an X-ray fluorescence (XRF) spectrometer.

*Data Analysis*

The data analysis model applied was Analysis of Variance (ANOVA) to evaluate the effect of aluminum composition on hardness and microstructural characteristics. Statistical analysis was performed using Minitab software.

## RESULTS AND DISCUSSION

### Result

*Raw Material Characteristics*

1. Chemical Composition of Iron Sand of Ampenan Beach

The results of XRF analysis of the iron sand of Ampenan Beach, Lombok, show the following chemical composition:

**Table 1.** Chemical Composition of Ampenan Beach Iron Sand

| **Elements/Oxides** | **Content (%)** |
|---|---|
| $Faith_3O_4$ | 74.5 |
| $Who_2$ | 12.3 |
| $Al_2O_3$ | 4.2 |
| $TiO_2$ | 3.8 |
| MgO | 2.1 |
| CaO | 1.8 |
| MnO | 0.9 |
| $P_2O_5$ | 0.4 |
| $TiO_2$ | 3.8 |

*Source: ASTM E18-20. (2020)*

The magnetite content ($Fe_3O_4$) of 74.5% indicates that the iron sand of Ampenan Beach has good quality for casting raw materials. The relatively high $TiO_2$ content (3.8%) is a characteristic of Indonesian iron sand and can contribute to the increased hardness of the final product.

2. Chemical Composition of Used Aluminum Cans

Analysis of the composition of used aluminum cans after cleaning shows:

**Table 2.** Chemical Composition of Used Aluminum Cans

| Elements | Content (%) |
|---|---|
| Al | 98.7 |
| Fe | 0.5 |
| The | 0.3 |
| Cu | 0.2 |
| Mg | 0.2 |
| Mn | 0.1 |

*Source: ASTM E18-20. (2020)*

The high purity of aluminum (98.7%) indicates that scrap cans can be used as an effective source of aluminum alloy in the casting process.

*Hardness Data Test Results*

The hardness test results for each heat treatment sample are presented in Table 3. The hardness value was measured three times for each heat treatment sample and test method.

**Table 3.** Hardness Data Brinell (HBN), Rockwell (HR), Vickers (HV)

| **Yes** | **Heat Treatment** | **Average HBN ($kg/mm^2$)** | **Average HR ($kg/mm^2$)** | **Average HV ($kg/mm^2$)** |
|---|---|---|---|---|
| 1 | Aneling (A) | 145.17c | 48.67b | 136.23c |
| 2 | Quenching (Q) | 254.92a | 72.00a | 228.99b |
| 3 | Normalising (N) | 189.94b | 54.33b | 341.96a |
| 4 | No Treatment (R) | 153.86c | 54.00b | 148.00c |

Remarks: *The number followed by the same letter in the same column is different from the 5% BNJ test.*

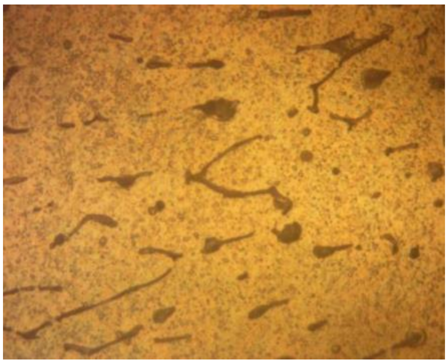
*Aluminum Composition and Microstructure Data*

**Table 4.** Aluminum Composition and Microstructure Data

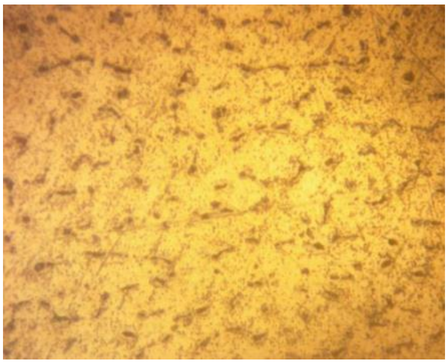
| Aluminum Composition (%) | Microstructural Characteristics | Average Grain Size (μm) | Main Phases Identified | Degree of Hardening |
|---|---|---|---|---|
| 0 | Rough, porous, non-homogeneous structure with large lamellar graphite | 50.0 | α-Fe, Graphite | Low |
| 2 | Smoother structure; initial formation of $Al_4C_3$ phase; grain boundaries become more pronounced | 38.5 | α-Fe, $Al_4C_3$ | Moderate |
| 4 | Denser and smoother microstructure; uniform phase distribution | 31.5 | α-Fe, $Al_4C_3$, $Fe_3Al$ | High |
| 6 | Smoothest and most homogeneous structure; dominant nodular graphite; strong interphase bonding | 25.0 | α-Fe, $Al_4C_3$, $Fe_3Al$ | Very High |
| 8 | Intermetallic phase agglomeration; slight grain coarsening observed | 27.5 | α-Fe, $Al_4C_3$, $Fe_3Al$ | High (incipient saturation) |

*Source: Microstructure Analysis in the Laboratory of the Faculty of Mechanical Engineering, University of Mataram*

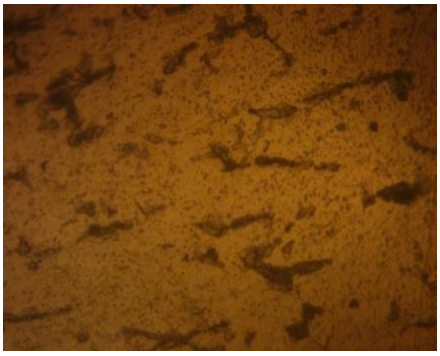
The following is a picture of the microstructure test results of each Aluminum composition:

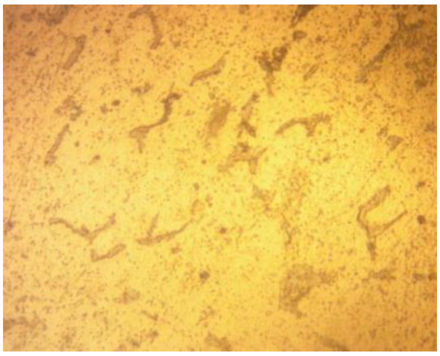


0% 1,000x



2% 1,000x


4% 1,000x


6% 1,000x

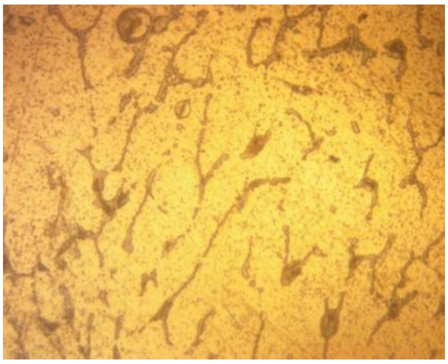

8% 1,000x

**Figure 1.** Results of Microstructure Analysis of Each Aluminum Composition with 1,000x Microscopic Magnification

**Discussion**

ANOVA test results for all three hardness methods (Brinell, Rockwell, and Vickers) consistently show that heat treatment has a very significant influence on the hardness of scrap aluminum can alloys and iron sand. This suggests that thermal manipulation can alter the microstructure of materials, thereby affecting their mechanical properties, particularly hardness. This can be proven by the results of the microstructure test presented in Figure 1.:

Based on the study results using the Brinell and Rockwell Methods, samples treated with Quenching (Q) consistently showed the highest average hardness values (HBN: 254.92 kg/mm$^2$, HR: 72.00 kg/mm$^2$). This is in line with the principle of quenching, which aims to produce very hard microstructures, such as martensite (if formed) or supersaturated solid solution phases, achieved through high-speed cooling rates. These phases inhibit the movement of dislocations, thereby increasing the material's hardness. The Normalising (N) treatment produces higher hardness than the Untreated (R) and Aneling (A) conditions, but still has the same significance as Quenching (Q). Normalization aims to improve grain size, making it smoother and more evenly distributed, and to eliminate internal stress. This process generally increases strength and hardness compared to as-cast conditions. In the Aneling treatment (A), the lowest hardness value was observed (HBN: 145.17 kg/mm$^2$, HR: 48.67 kg/mm$^2$), even slightly below or equivalent to the No Treatment (R) condition (HBN: 153.86 kg/mm$^2$, HR: 54.00 kg/mm$^2$). This corresponds to the purpose of annealing, which is to soften the material, remove residual stress, and enlarge the grain size, all of which contribute to a decrease in hardness.

**Table 5.** Research Results on the Brinell and Rockwell Methods

| No | Heat Treatment Type | Average HBN (kg/mm$^2$) | Average HR (kg/mm$^2$) | Average HV (kg/mm$^2$) |
|---|---|---|---|---|
| 1 | Annealing (A) | 145.17$^c$ | 48.67$^b$ | 136.23$^c$ |
| 2 | Quenching (Q) | 254.92$^a$ | 72.00$^a$ | 228.99$^b$ |
| 3 | Normalizing (N) | 189.94$^b$ | 54.33$^b$ | 341.96$^a$ |
| 4 | No Heat Treatment (R) | 153.86$^c$ | 54.00$^b$ | 148.00$^c$ |

In Vickers' method, the trend is slightly different. The Normalising (N) treatment showed the highest average hardness value (HV: 341.96 kg/mm$^2$), even surpassing the Quenching (HV: 228.99 kg/mm$^2$) treatment. This difference is significant and interesting. Vickers hardness measures hardness at a more microscopic scale, making it highly sensitive to local microstructural characteristics, such as grain size, hardener phase distribution, and the presence of precipitates. The presence of a higher standard deviation in the Normalising sample suggests the possibility of greater microstructural heterogeneity; however, on average, this method demonstrates the success of normalisation in substantially increasing local hardness. It can be inferred that normalization of this specific alloy may result in an optimal phase or precipitate distribution at the microscale, as measured by the Vickers hardness test. Just like the other methods, Aneling (A) still showed the lowest hardness in the Vickers test.

The addition of aluminum as an alloy element in the iron sand casting process at Ampenan Beach has a significant impact on the material's hardness. Based on the results of the BNJ test at a 5% confidence level, it is known that an increase in aluminum content from 0% to 6% results in an increase in hardness value. The low initial hardness value (0% Al) is attributed to the microstructure, which remains rough, heterogeneous, and dominated by large lamellar graphite that acts as a stress concentration point (Groover, 2020). As the aluminum composition increases, the microstructure undergoes a significant transformation, characterized by the formation of intermetallic phases such as $Al_4C_3$ and $Fe_3Al$, as well as changes in the morphology of graphite to a nodular form. These two phases are known to have high hardness and distribute loads more evenly within the metal matrix, thereby increasing the overall hardness of the material (Chen et al., 2020). In addition, the grain refinement effect due to aluminum acting as a nucleator resulted in a decrease in grain size from 50 µm (0% Al) to 25 µm (6% Al), which is in line with Hall-Petch's theory, which states that hardness increases as the grain size decreases (Nurjaman, 2019).

However, when the aluminum content reaches 8%, the hardness value drops/saturates. This is due to over-alloying, which causes the $Al_4C_3$ phase to cluster and not spread homogeneously. Uneven phase distribution leads to the formation of weak zones within the structure, thereby reducing the material's resistance to deformation.

*Limitation*

This study is limited to aluminum additions of up to 8% and focuses on hardness testing and microstructural analysis, while other mechanical properties such as toughness and wear resistance were not investigated.

## CONCLUSION

The findings of this study indicate that the addition of aluminum significantly enhances the hardness of iron sand castings, with an optimal composition of 6% aluminum resulting in the highest Brinell hardness, representing a 28.8% improvement over the control sample. This enhancement is closely related to the refinement of the microstructure, evidenced by a reduction in average grain size from 50.0 µm (at 0% Al) to 25.0 µm (at 6% Al). At this optimal composition, the microstructure reveals a ferrite matrix with a uniform distribution of hardening phases such as $Al_4C_3$ and $Fe_3Al$, as well as a morphological transformation of graphite from lamellar to nodular. These changes collectively contribute to increased hardness through mechanisms that include grain refinement, precipitation hardening, and modification of graphite morphology. Furthermore, the strong correlation between grain size reduction and hardness enhancement aligns with the Hall-Petch relationship ($R^2$ = 0.92). However, the introduction of aluminum beyond 6% led to a decline in hardness, likely due to over- alloying effects that caused carbide phase agglomeration and reduced uniformity in phase distribution.

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## AUTHOR CONTRIBUTION STATEMENT

The Authors conducted the research design, experiments, and manuscript preparation, Sinarep performed data analysis and result interpretation, and Anak Agung Alit Triadi supervised the study and reviewed the final manuscript.

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