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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

Iron sand from Ampenan Beach, Lombok, which contains 74.5% Fe_3O_4, holds significant potential as a local raw material for metal casting. However, its mechanical properties, particularly hardness and microstructural uniformity, often require improvement for industrial applications. This study aims to investigate the effect of adding used aluminum can alloy on the hardness and microstructure of iron sand casting. The experiment was designed 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 tests were conducted using Brinell, Rockwell, and Vickers methods, while microstructure was analyzed through optical microscopy. The results showed that the addition of aluminum significantly increased material hardness, with the optimal result achieved at a 6% aluminum composition, resulting in a 28.8% increase in Brinell hardness compared to the control sample. Microstructural refinement was observed, with a grain size reduction from 50.0 μm at 0% Al to 25.0 μm at 6% Al, accompanied by the formation of a ferrite matrix with evenly distributed Al_4C_3 and Fe_3Al phases and a transformation in graphite morphology from lamellar to nodular. However, an excess of aluminum (8%) reduced hardness due to over-alloying and phase clustering. These findings suggest that optimizing the composition of recycled aluminum alloys can enhance the mechanical performance of locally sourced cast materials, supporting sustainable practices in metallurgy.

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). 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). Therefore, the addition of alloying elements has emerged as a promising strategy to enhance the mechanical behavior and microstructural quality of cast products.

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). 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).

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). 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). 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).

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). 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).

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). 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

This research was conducted in June and July 2025 and located at Ampenan Beach, Ampenan District, Mataram City, West Nusa Tenggara. The experimental design employed a Completely Randomized Design (CRD) with variations in the composition of aluminum alloy as the treatment factor, specifically 0%, 2%, 4%, 6%, and 8%. Each treatment was repeated three times, resulting in a total of 15 trials.

The tools used include smelting furnace: induction type crucible furnace with a capacity of 5 kg, mold: silica sand mold with dimensions of 150mm x 25mm x 25mm, preparationequipment: cutting *machine*, mounting press, grinding machine, polishing machine, measuring tool: digital scale (accuracy 0.1g), thermocouple type K, hardness testing tool: Universal Hardness Tester Brinell HB-3000, Olympus BX51M and SEM-EDS Zeiss EVO MA 10 optical microscopes, and analysis equipment: XRF spectrometer for chemical composition analysis. The materials used include; iron sand from Ampenan Beach, Lombok NTB as much as 10 kg, used aluminum cans (beverage cans) as much as 2 kg, metallurgical coke as a reduction fuel, flux in the form of CaO and SiO_2 for slag formation, samplepreparation: epoxy resin, sandpaper (grid 240, 400, 600, 800, 1000, 1200), alumina powder 1µm and 0.3µm, and etching material: Nital 2% solution (2ml HNO_3 + 98ml ethanol).

The sampling technique employs a grid sampling method with nine collection points. The data collection techniques include hardness data: HB values from 5 test points per specimen, Microscopic data: Microstructure drawings at various magnifications, Composition data: EDS analysis results for element distribution, Initial iron sand chemical composition data (XRF results), Waste canned aluminum composition data, Smelting and casting process parameters, Environmental conditions during the study. The analysis model used is *Analysis of Variance* (ANOVA), which is performed using Minitab software.

RESULTS AND DISCUSSION

1. Raw Material Characteristics

a. 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

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.

b. 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.

2. 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/mm²)	Average HR (kg/mm²)	Average HV (kg/mm²)
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.*

3. Aluminum Composition and Microstructure Data

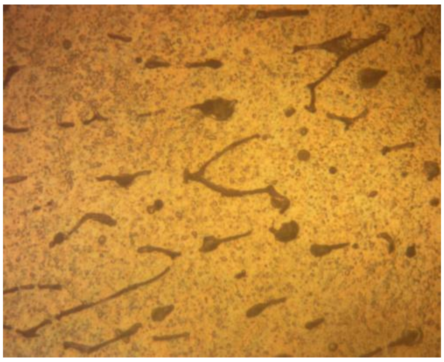
Table 4. Aluminum Composition and Microstructure Data

Composition of Al	Characteristics of Microstructures	Average Grain Size	Main Phase	Degree of Violence

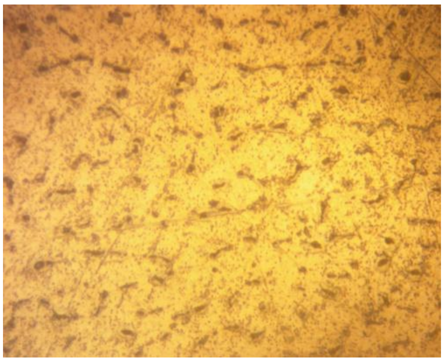
0%	Rough, porous, non-homogeneous, large lamellar graphite structure	50µm	α-Fe, Graphite	Low
2%	Starting smoothly, a small Al_4C_3 phase appears, and grain boundaries are more pronounced	38.5 µm	α-Fe, Al_4C_3	Keep
4%	The microstructure is denser and smoother, and the phase distribution is even	31.5 µm	α-Fe, Al_4C_3, Fe_3Al	The higher it is
6%	The smoothest and homogeneous nodular graphite, hardening phase is dominant, strongly bonded,	25 µm	α-Fe, Al_4C_3, Fe_3Al	Tall
8%	Agglomeration/ Intermetallic phase clumping occurs, slightly coarse again	27.5 µm	α-Fe, Al_4C_3, Fe_3Al	Still high/starting to get saturated

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

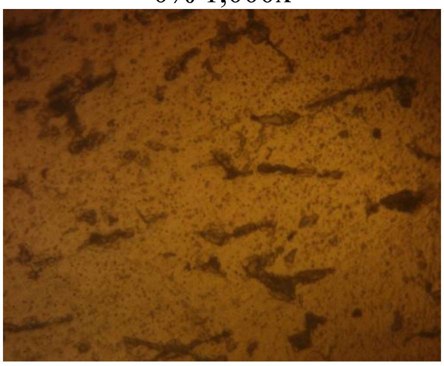
The following is a picture of the microstructure test results of each Aluminum composition:



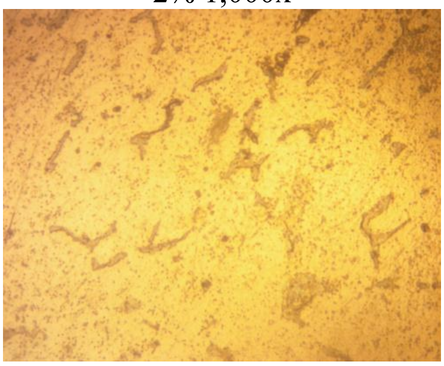
0% 1,000x



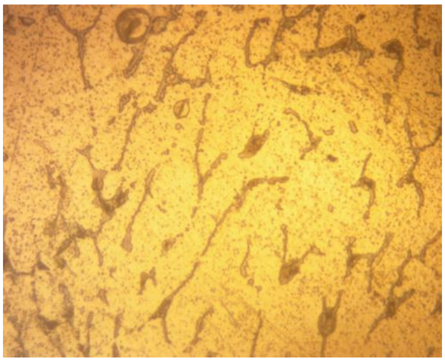
2% 1,000x



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/mm², HR: 72.00 kg/mm²). 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/mm², HR: 48.67 kg/mm²), even slightly below or equivalent to the No Treatment (R) condition (HBN: 153.86 kg/mm², HR: 54.00 kg/mm²). 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

Yes	Heat Treatment	Average HBN (kg/mm²)	Average HR (kg/mm²)	Average HV (kg/mm²)
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

In Vickers' method, the trend is slightly different. The Normalising (N) treatment showed the highest average hardness value (HV: 341.96 kg/mm²), even surpassing the Quenching (HV: 228.99 kg/mm²) 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 (Vijaya et al., 2014). 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.

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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