UDC 669.715:621.785
DOI: 10.15587/1729-4061.2026.359420

IDENTIFYING THE HARDNESS LEVEL OF RECYCLED ALUMINUM WITH THE ADDITION OF CU POWDER THROUGH A MELTING MECHANISM BELOW THE MELTING POINT AND PRECIPITATION REINFORCEMENT

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The object of this study is the alloy of Al-Cu with recycled aluminum and the addition of copper powder. The current problem is the use of aluminum waste, which is still very limited, and the mechanical properties of aluminum waste are declining, so material manufacturing engineering technology is needed to process the aluminum waste into new materials used for various applications, so that it can reduce the energy consumption of the manufacturing process and improve mechanical properties.

This study aims to increase alloy hardness by adding recycled aluminum in the form of copper powder, using sub-melting-point processing and precipitation. It addresses rising industrial demand for aluminum and the need for superior mechanical properties, focusing on eco-friendly products, recycled materials, and energy-saving smelting practices. Results show that aluminum combined with copper powder can be processed below copper's melting point via diffusion in $Al_{90}Cu_{10}$ and $Al_{95}Cu_5$ at 1000°C and 1050°C, respectively, with both aged at 300°C. Hardness increased from 25 HBW to 94 HBW in $Al_{90}Cu_{10}$ over the temperature range of 1000°C to 1050°C.

This research addresses the growing problem of aluminum waste by recycling it into products with enhanced mechanical properties. Adding copper powder and melting at a low temperature reduces energy use during smelting. The aging strengthening mechanism increases the hardness of aluminum alloys, meeting industrial needs. The increased hardness and wear resistance of the recycled products of AL-Cu alloys developed in this study can have the potential to be applied to non-structural mechanical elements that have an impact on environmentally friendly and energy-efficient manufacturing processes

Keywords: aluminum recycling, mechanical properties, Al Cu precipitation, below melting point

Received 18.03.2026
Received in revised form 01.06.2026
Accepted date 10.06.2026
Published date 30.06.20226

How to Cite: *Erwin, E., Pratama, J., Sugiyanto, D., Chan, Y., Wiradinata, T. A., Febrian, M. A., Ariz, D. A. (2026). Identifying the hardness level of recycled aluminum with the addition of cu powder through a melting mechanism below the melting point and precipitation reinforcement. Eastern-European Journal of Enterprise Technologies, 3 (12 (141)), 18–27. https://doi.org/10.15587/1729-4061.2026.359420*

1. Introduction

Global concerns about environmentally friendly products continue to grow, especially in industries producing metal alloys. Aluminum is widely used in the automotive, aviation, and manufacturing industries. Fierce competition in the aluminum industry demands products that do not harm the environment. Reliable quality is mandatory across industries.

High costs of mining, refining, and smelting have prompted ongoing efforts to reduce expenses. One strategy is to use leftover or recycled aluminum products; however, it is essential to ensure that the alloy's mechanical properties still meet product requirements.

One of the main cost drivers in the smelting industry is energy use. To lower this cost, it is necessary to develop a diffusion-based mechanism that melts the alloy below the melting point of its elements. Smelting below the melting point can produce recycled products and reduce energy consumption. To maintain excellent mechanical properties, a reinforcing element, namely copper in the form of a belt, should be added so that it dissolves easily in the aluminum alloy solution. Copper is known to improve the performance of aluminum alloys. Therefore, this study must demonstrate the impact of adding copper below the melting point of aluminum on the mechanical properties of the resulting melt. Recycled aluminum products are strengthened with copper powder through precipitation after melting, resulting in optimal reinforcement for smelted and molded products. These results address industry challenges in developing innovations, such as diffusion mechanisms, sub-melting-point processing, and precipitation strengthening, for environmentally friendly, high-quality products.

Therefore, research on development of improving the mechanical properties of alloys from waste aluminum with the addition of reinforcing materials such as copper powder and processed by melting below the melting point to reduce energy consumption and strengthened by the addition of an aging process to increase strength is relevant, this is what the industry needs in the use of recycled materials with an eco-friendly material approach and has excellent mechanical properties.

2. Literature review and problem statement

Presents the results of research, the precipitation-reinforcement mechanism improves the mechanical properties of AlCu alloys by inhibiting dislocation motion and increasing hardness [1]. Shown, that during precipitation, atoms separate from solid solutions to form phases that restrict dislocation movement [2]. Compositional variations during casting affect mechanical properties and precipitation, supporting homogeneous microstructures [3]. Adding elements such as Mn, Er, and Zr through precipitation and heat treatment yields a uniform grain size and enhances mechanical properties [4]. Precipitation hardening alters strain in AlCu alloys [5]. But there were unresolved issues related to consistent temperature control during precipitation must be confirmed to address recycling challenges in aluminum-copper alloys and enhance mechanical properties to meet industry needs. A way to overcome these difficulties can be increasing the strength of recycled aluminum materials, one approach is to develop manufacturing technology based on a precipitation mechanism, as part of efforts to meet industry needs for producing recycled materials with excellent strength.

Shown, that controlling the aging temperature can improve grain size, evenly distribute deposits, and alter the microstructure of AlCu alloys [6]. Low aging temperatures increase strength, smooth deposits, and enhance alloy homogeneity [7]. Thermomechanical treatment produces smaller grain sizes [8]. Increased yield strength and hardness result from fine particle deposition; optimizing temperature reduces alloy fatigue [9]. The reason for this may be temperature control during casting, especially permanent casting via precipitation, is needed to increase the hardness of AlCu alloys, particularly those from recycled aluminum. However, all this suggests that it is advisable to conduct a study on produce environmentally friendly recycled aluminum materials and to lower energy consumption by optimizing the melting temperature below the melting point of reinforcing materials, such as copper, thereby reducing material procurement costs and energy consumption.

There were unresolved issues related to the current problem is the lack of research into the reprocessing of aluminum waste or scrap into new products to meet industrial needs. This approach was used, not only can the problem of using recycled materials be minimized, but the issue of smelting energy consumption can also be minimized by optimizing the melting temperature below the melting point of alloy elements, and the reuse of recycled materials also reduces the process of taking materials from natural resources and refinery processes that consume a lot of energy. However, all this suggest that it is advisable to conduct study on an alloy-strengthening mechanism is required through the addition of reinforcing elements, such as copper powder and precipitation, to produce a high-quality product with superior mechanical properties.

3. The aim and objectives of the study

The aim of this study is to identify the influence of several variations in melting temperature and composition of copper addition through smelting below the melting point, with the precipitation mechanism can increase the hardness of fabricated AlCu alloys to meet industrial needs.

To achieve this aim, the following objectives were accomplished:

– to performing the aluminum alloy melting process by adding copper powder below the copper melting point with different composition variations;

– to perform a mechanism to strengthen the precipitation of the casting process through permanent casting with the same temperature for both variations of the addition of copper powder elements, and its effect on the characteristics of microstructures reinforced by precipitation mechanisms;

– to perform Brinell hardness testing to ensure that the hardness level increases with the addition of processed copper elements below the melting point, with a precipitation mechanism.

4. Materials and methods

The object of this study is the alloy of Al-Cu with recycled aluminum and the addition of copper powder. This study observed the microstructure and hardness level after the melting process below the melting point of copper and aging treatment. Recycled aluminum and copper powders are processed for manufacturing and, after several strengthening mechanisms, such as precipitation, are further analyzed for material characteristics, including alloy hardness. The manufacturing or smelting process for alloy materials is carried out below the alloy's melting point. The main hypothesis of this study is that the development of material manufacturing technology for recycled aluminum waste, combined with copper powder, by melting below the melting point of the reinforcing element and using the precipitation mechanism, can increase the alloy's hardness.

The assumption used in this study is that the addition of copper powder during the smelting process is evenly distributed in the aluminum matrix after the stirring and heat treatment process. The aging temperature is also assumed to be uniform in all parts of the specimen during the precipitation process. The chemical composition of recycled aluminum is assumed to be relatively homogeneous, as is the composition of the material used. The response to the mechanical properties of the alloy is assumed from the degree of hardness produced. The effect on alloy formation is not affected by temperature fluctuations and heat loss during the melting process.

The simplification applied in this study is that the use of optical microscopes with a magnification of 100x and 200x is limited to the observation of microstructure characterization. Analysis of mechanical properties is only carried out on the results of hardness tests. The precipitation mechanism was analyzed from the results of microstructure observation and thermodynamic simulation without direct identification of the phase using SEM-EDS and XRD. The variation used in this study only used two composition variations, namely the addition of Cu5% and Cu 10%, with two variations of melting temperature at 1000°C and 1050°C. Determination of constant temperature in the aging process was focused on observing the influence on Cu composition and melting temperature.

Pure aluminum material 1100 is used as the primary material of the alloy has a composition according to JIS H 4000 standard of iridescent from: Aluminum (Al): ≥ 99.00%, Silicon (Si): ≤ 0.95%, Iron (Fe): ≤ 0.95%, Copper (Cu): ≤ 0.20%, Zinc (Zn): ≤ 0.10%, Manganese (Mn): ≤ 0.05%, Beryllium (Be) ≤ 0.15%. As a reinforcing material, powdered copper is added, conforming to JIS H 2501, with a composition of copper (Cu): 99% and Phosphorus (P): 0.01%–0.4%. The JIS H 4000 standard refers to the use of aluminum 1100 material [10], and the JIS H2501 standard refers to the use of copper powder material as a reinforcing [11]. The following is the initial composition of aluminum and copper powder used in this study. The following are the elements of the experimental raw materials of this research, as stated in Table 1.

Table 1

Elements of raw material in research

Material	Elements in [%weight]						
	Al	Cu	Si	Fe	Mn	Zn	Pb
Al 1100	Balance	0.05	0.5	0.5	0.05	0.1	–
Cu Alloy	–	Balance	–	–	–	–	0.0235

The free variables in this study are the variation of the element aluminum 90% and 95%, the element Cu 5% and 10%, the bound variable of this study is yield casting based on the composition and temperature control, the precipitation mechanism and the hardness level of aluminum and copper alloys, and the controlled variable is the melting temperature varied by 1000°C and 1050°C, and the temperature aging is 300°C and cooling time with water for 60 seconds. The analysis method used to assess the relationship between variables employs statistical regression to estimate the determination coefficient, thereby yielding more accurate results. Table 2 explains the variations of alloys to be processed in manufacturing, along with the melting and aging temperatures.

Table 2

Alloy composition, melting, and aging temperature

Alloy	Smelting temperature (°C)	Aging temperature (°C)
Al90Cu10	1000	300
Al95Cu5	1000	300
Al90Cu10	1050	300
Al95Cu5	1050	300

Table 2 shows that variations in Al–Cu alloys with Cu compositions of 5% and 10%, melted at temperatures between 1000°C and 1050°C and aged at 300°C, can yield patterns in strength characteristics and final microstructures, especially at lower melting temperatures and higher copper powder additions. The temperature used in smelting is below the copper melting point of 1085°C, achieved with an electric induction furnace followed by manual stirring. It is poured into a permanent cavity in the aging and cooling process using water. Increasing the melting temperature from 1000°C to 1050°C alters the distribution of Cu precipitates in the aluminum matrix and can improve grain homogeneity, thereby increasing the alloy›s hardness and ductility. The aging temperature of 300°C contributes to strengthening the alloy by forming a finer precipitate phase, thereby achieving more optimal mechanical properties.

The electric induction furnace was designed and fabricated by the research team with a capacity of 5 Kg and a maximum power temperature of 1300°C, with a power of 3000 Watts, and supported by additional equipment such as containers or crucibles, permanent molds, cast pliers, gas torches, scales, temperature measuring instruments, stopwatches, and work safety equipment. The initial stage of the experiment was weighing to determine the weight fraction based on the variation in the weight composition of aluminum and copper powder, then setting the temperature according to the specified temperature variation. The aluminum material is placed in the furnace, and within 5 minutes, it has melted. Gradually add the copper powder and manually stir it into the aluminum-copper alloy solutions. Heating is carried out in a permanent mold before pouring, and the mold temperature is measured with a thermometer. Aluminum and copper alloy laurels are poured into permanent molds, and cooling is achieved by dipping the specimens into water. The microstructure micro test uses the Olympus BX41M-LED brand Inverted Metallurgical Microscope with ASTM E3 [12] and ASTM E407 [13] test methods. The microstructure test equipment has a digital camera system to magnify up to 200x to see the grain limits, phase distribution, and also the morphology of the Al-Cu alloy. The specimen is finished, and then microstructure testing at 100–200x using an optical microscope. Hardness testing using the LCB3100 Brinell Load Cell Hardness tool. The tester conforms to ASTM E10 [14]. A steel ball indenter is used in a controlled loading system to determine the Brinell hardness (HBW) in Al-Cu alloy specimens. Details of the dissolution process are shown in Fig. 1. Scheme of the dissolution process and precipitation mechanism of aluminum and copper alloys.

The scheme in Fig. 1 above shows that this study analyzes the influence of variations in aluminum and copper composition, as well as temperature control during melting and aging, on casting yield, precipitation mechanism, and alloy hardness. Melting is carried out in an Electric induction furnace at a temperature below the copper melting point, followed by manual stirring, pouring into a permanent mold during aging, and water cooling. The specimen underwent a finishing process before microstructure observation was carried out at a magnification of 100–200x using an optical microscope on the specimen with the lowest temperature control and a larger copper addition composition, as well as hardness testing on the entire specimen using the Brinell method, regression statistical analysis was used to determine the relationship between variables and to see the value of the highest determination coefficient to determine the strength value of the alloy best.

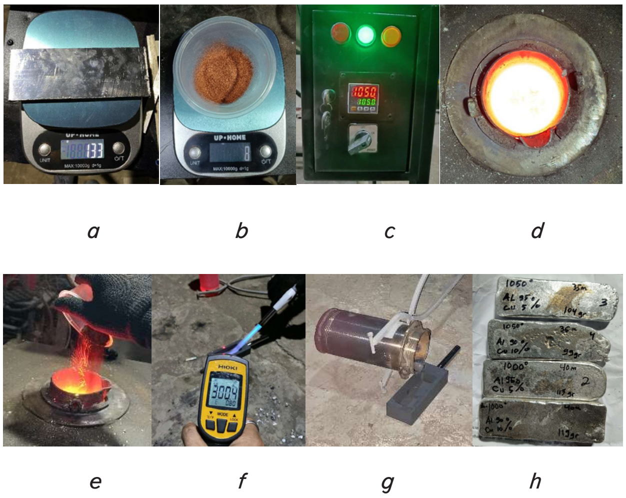


Fig. 1. Scheme of the smelting process of aluminum and copper alloys and precipitation mechanisms: *a* – weighing of aluminum scrap; *b* – weighing of copper powder; *c* – control of melting temperature; *d* – aluminum smelting process; *e* – copper powder adding process; *f* – precipitation process; *g* – pouring process; *h* – final product

5. Result of manufacturing process, microstructure, and hardness testing

5. 1. AlCu melting manufacturing process and precipitation mechanism

The results of the AlCu aluminum alloy smelting process are clearly shown in Table 3 below, which includes the initial weight of the aluminum scrap, the final weight after copper powder addition, and the slag results linked to the yield casting.

Table 3

Weight and slag of AlCu alloy

Alloy	Initial weight (g)	Final weight (g)	Initial and final weight difference (g)	Yield casting (%)	Weight of slag (g)
Al90Cu10 (a)	139	99	46	70	43
Al90Cu10 (b)	139	119	20	85	19
Al95Cu5 (a)	139	113	26	80	26
Al95Cu5 (b)	139	104	35	74	46

Table 3 shows that the Al90Cu10 alloy has a higher casting yield and less slag than the Al95Cu5 alloy at both 1050°C and 1000°C. Adding 10% Cu increases solubility, reduces slag, and improves yield. In contrast, adding 5% Cu raises the slag and lowers casting yield. Raising the melting temperature from 1000°C to 1050°C increases solubility and further reduces slag, providing optimal fluidity at higher Cu levels [3], thereby enhancing casting quality. Oxidation increases slag and reduces casting efficiency with lower Cu additions to the aluminum alloy.

The precipitation mechanism in this study uses a temperature of 300°C in the AlCu alloy; simulation of phase behavior and precipitation kinetics is carried out in the Al-90Cu10 alloy. An explanation of the formation of the Al2Cu phase in the aging process was used in this simulation, and the effect on the level of hardness. The simulation results clearly show that the aging temperature of 300°C has an impact on the Al2Cu precipitation process as an inhibitor of dislocation movement, thus providing an increase in the hardness of AlCu alloy materials. Thermodynamic and precipitation-kinematics calculators are used to determine the volume fractions of the formed phases, such as the FCC_A1 main phase (dissolved solid aluminum) and Al2Cu_C16 deposits. From the simulation results, the sediment density, the number of deposits, and the distribution of sediment size resulting from temperature changes affect the growth of nucleation and sediment during the heating process. The results of this simulation are relevant to explain the mechanism of precipitation in AlCu alloys and the heating time affecting the formation of microstructures that are very important for the optimization of heat treatment in metals, in improving the mechanical properties of the alloy.

Fig. 2 explain the correlation of volume fractions in the two main phases, namely Al_2Cu_C16 and FCC_A1, in temperature control. The increase in temperature from 300°C to 350°C has significantly increased the volume fraction of Al_2Cu_C16 and decreased the FCC_A1 phase. This explains the precipitation transition of the solid solution phase that forms the precipitation in the alloy.

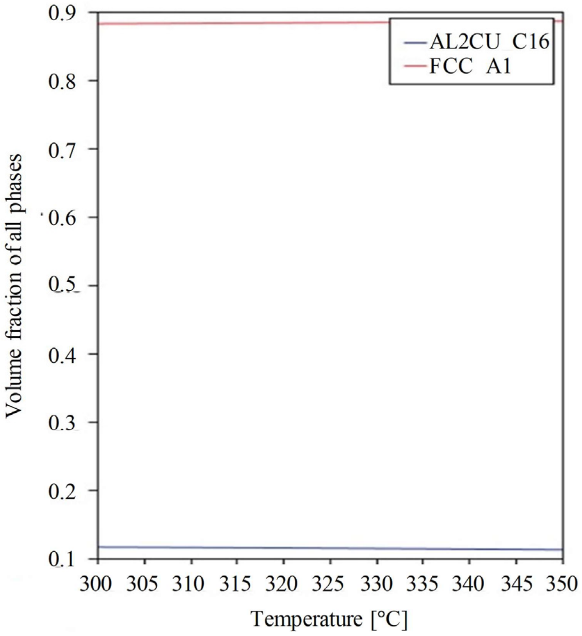


Fig. 2. Precipitation volume and temperature fractions

Fig. 2 describe the volume fraction in the two main phases at a temperature of 300°C to 350°C in the heating process. Phase FCC_A1, which is a solid solution of aluminum, has a decreasing fraction from 0.8 to 0.1 as the temperature increases. In the intermetallic deposition phase, Al_2Cu_C16 experienced an increase in fractions with volumes from about 0.1 to 0.6 at high temperatures. This explains that the phase transformation that occurs upon heating, in which the Al_2Cu_C16 deposits form the solid phase of the aluminum solution, contributes to the increase in the hardness of the AlCu alloy.

Simulations of sediment density during aging showed an initial increase at the beginning of nucleation, followed by a decrease during precipitation, which confirmed the particle size.

The visualization of precipitate density over time during the aging process in Fig. 3 shows an initial exponential increase in nucleation, which then peaks and decreases as precipitate growth consolidates particle size.

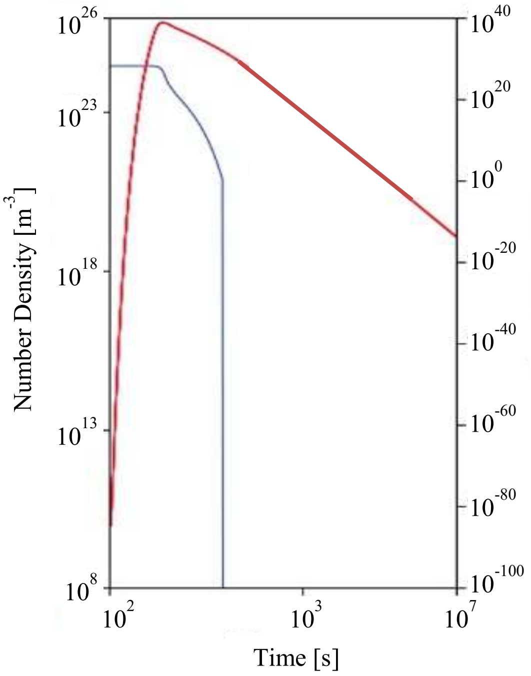


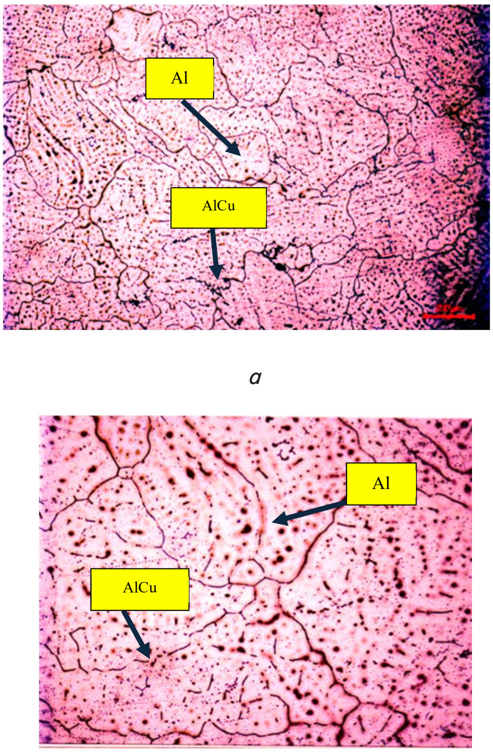
Fig. 3. Relationship of precipitation nuclei, density, and time

Fig. 3 describes the nucleation movement of Al_2Cu_C16 precipitation in the aging process in units of seconds. The increase in the initial aging process reaches its maximum before the decrease; this describes the union of particles and their growth, which provides a level of density. The graph illustrates the evolution of the deposit, from rapid nucleation to the growth of large, more stable particles in the microstructure.

The correlation between aging temperature and heating time affects the microstructure of AlCu alloys, as shown by simulation results. Elevated aging temperatures increase nucleation rates and Al_2Cu_C16 deposition, which decreases the fraction of the FCC_A1 phase in solid solutions. The aging process increases sediment density and particle size, leading to reduced growth and particle consolidation. Changes in mechanical properties due to precipitation mechanisms also alter the microstructure. The kinetic relationship between aluminum alloys and manufacturing processes confirms that controlling aging temperature and mechanical properties strongly influence outcomes.

5. 2. AlCu alloy microstructure test results

The following is a picture of the Al90Cu10 Alloy Microstructure in Fig. 4. Identify the microstructure characteristics of Al-Cu recycled alloys from the casting results after the stages of the melting and aging process by conducting detailed morphological observations using an optical microscope. Observations were made at 100x magnification in Fig. 4, *a* and 200x magnification in Fig. 4, *b*. The results of the microstructure test at 100x magnification of the Al90Cu10 alloy show that the Al matrix is lighter in color. At the same time, the darker area around the grain boundary is occupied by Cu. The characteristics of the Al and AlCu matrix as seen in Fig. 4, *a*. The test results at 200x magnification show that the morphology of the Al_2Cu compound is clearer, with the particles forming a short-rod plane. The spread of intermetallic phases in the AlCu alloy increases its hardness, as shown in Fig. 4, *b*.



a

b

Fig. 4. Al90Cu10 alloy microstructure: *a* – Al element dominates and AlCu alloy 100x magnification, *b* – Al element dominates and AlCu alloy 200x magnification

The microstructure image of the alloy Al90Cu10 confirms that the grain boundary is closed, as indicated by a thick black line. The grain boundary is clearly visible, showing the separation of crystalline grains. The lighter-colored image depicts the dominance of aluminum, while the darker region is an AlCu alloy. Visually, the dark lines cover the grain and the relatively small grain size characteristic of aluminum and copper alloys.

5. 3. Hardness test results

The results of the Brinell hardness test (HBW) showed that the Al alloy with 10% and 5% copper powder additions, with melting temperatures below 1000°C and 1050°C, and an aging temperature of 300°C. The following is Table 4 of the Brinell hardness test results.

Table 4

AlCu alloy hardness test results

Alloy	Casting temperature (°C)	Precipitate temperature (°C)	Hardness value (HBW)	Average (HBW)
Al90Cu10	1000	300	25	25
			27	
			26	
			22	
			25	
Al95Cu5	1000	300	45	42
			43	
			41	
			40	
			41	
Al95Cu5	1050	300	55	54
			54	
			54	
			55	
			54	
Al90Cu10	1050	300	85	94
			87	
			96	
			102	
			98	

The Table 4 above shows that the Al90Cu10 alloy with a melting temperature of 1000°C and an aging temperature of 300°C produces a hardness of 25 HBW, whereas a melting temperature of 1050°C yields a higher hardness of 85–102 HBW, with an average of 94 HBW. Al95Cu5 alloy at a melting temperature of 1000°C and an aging temperature of 300°C has an average hardness of 42 HBW, rising to 54 HBW. This is influenced by the increase of 1050°C and the addition of more copper powder. Another significant increase occurred in the alloy Al90Cu10, with hardness rising from 25 HBW to 94 HBW and the melting temperature increasing from 1000°C to 1050°C. In the Al95Cu5 alloy, the Brinell hardness increased from 42 HBW to 54 HBW, with the melting temperature rising from 1000°C to 1050°C.

The results of this study indicate that recycled aluminum can be melted by adding copper powder below the melting point of the element with the highest melting point, copper. This smelting process is carried out with two compositions: 5% and 10% copper powder. The smelting results showed differences in the alloy and slag weights, which were affected by composition and temperature. The correlation between the varied alloy composition, melting temperature and slag is illustrated in the trend in Fig. 5 below.

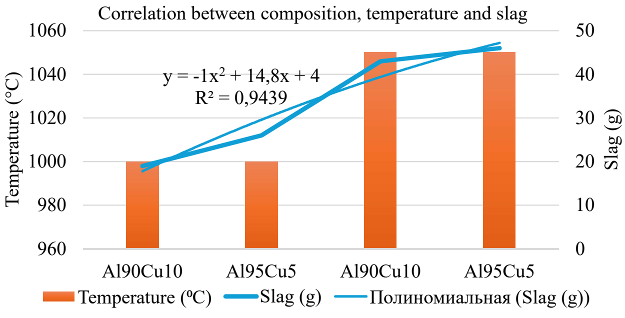


Fig. 5. Polynomial regression of slag weight

The determination coefficient (R^2) of 0.9439 indicates a significant relationship between variable temperature and slag weight in the AlCu alloy. This shows a correlation between variation in slag weight and the composition of Al-Cu alloys, as well as their melting temperature. Rising temperatures and decreasing Cu levels can increase the amount of slag. Optimization of melting temperature in AlCu alloys affects the amount of slag produced, and this has the potential to provide input for the industry to control temperature and composition to increase production targets.

The change in the alloy's hardness is shown by the increase in melting temperature when copper powder is added to aluminum. In AlCu alloys, at 1000°C, low hardness results from reduced sediment formation. When the melting temperature reaches 1050°C, hardness increases significantly due to optimal strengthening and higher melting temperatures. The hardness increases further because copper deposited in aluminum enhances precipitation strengthening, and, importantly, a higher copper content continues to boost the alloy›s strength. Fig. 6 shows the relationship between the melting temperature and the hardness test results.

Fig. 6 shows increased dislocation resistance and hardness, both influenced by melting temperature and copper concentration, which form fine, coherent precipitates in the AlCu matrix. Precipitation hardening hinders dislocation movement, increasing hardness and strength. This is evident from heat-treatment trends and alloy composition. Changes in melting temperature and heat treatment alter aging, thereby increasing strength and hardness [15].

The hardness test has been re-verified using the Brinell hardness test results, as shown in Table 4, so that all data shown in Fig. 4 are sourced from Table 4. A significant relationship between alloy composition, melting temperature, and hardness level in AlCu alloys is illustrated in Fig. 7. The increase in the alloy's mechanical properties is influenced by its copper content [16]. The rise in melting temperature, the addition of copper, and higher Brinell hardness all support this relationship, as indicated by the determination coefficient $R^2 = 0.9789$ from second-order polynomials. This confirms that the hardness level of AlCu alloys is significantly and nonlinearly impacted.

AlCu alloys confirm that the results of this experiment are influenced by thermal variables. The distribution of the Cu element in alloys and microstructures is heterogeneous due to its low diffusion rate at 1000°C, resulting in a hardness of 25 HBW in the Al95Cu5 alloy. At a temperature increase of 1050°C, the hardness increases by up to 94 HBW, equivalent to 276% in the Al90Cu10 alloy. In the Al95Cu5 alloy, the hardness increases by 32% to 54 HBW. This occurs due to the high metal density, as the grain-smoothing and precipitation process at 300°C makes the AlCu alloy more homogeneous. The 60-second water-cooling process affects the microstructure and coarse granules from the fine deposits, inhibiting dislocation and increasing overall hardness, which is further enhanced with a higher 10% Cu composition. The results of applying the precipitation-reinforcement mechanism indicate that temperature-aging control in permanent castings can increase the hardness of aluminum and copper alloys. This is evidenced by the results of the Brinell test, which can increase the alloy's hardness through material manufacturing technology, including melting below the melting point and precipitation mechanisms.

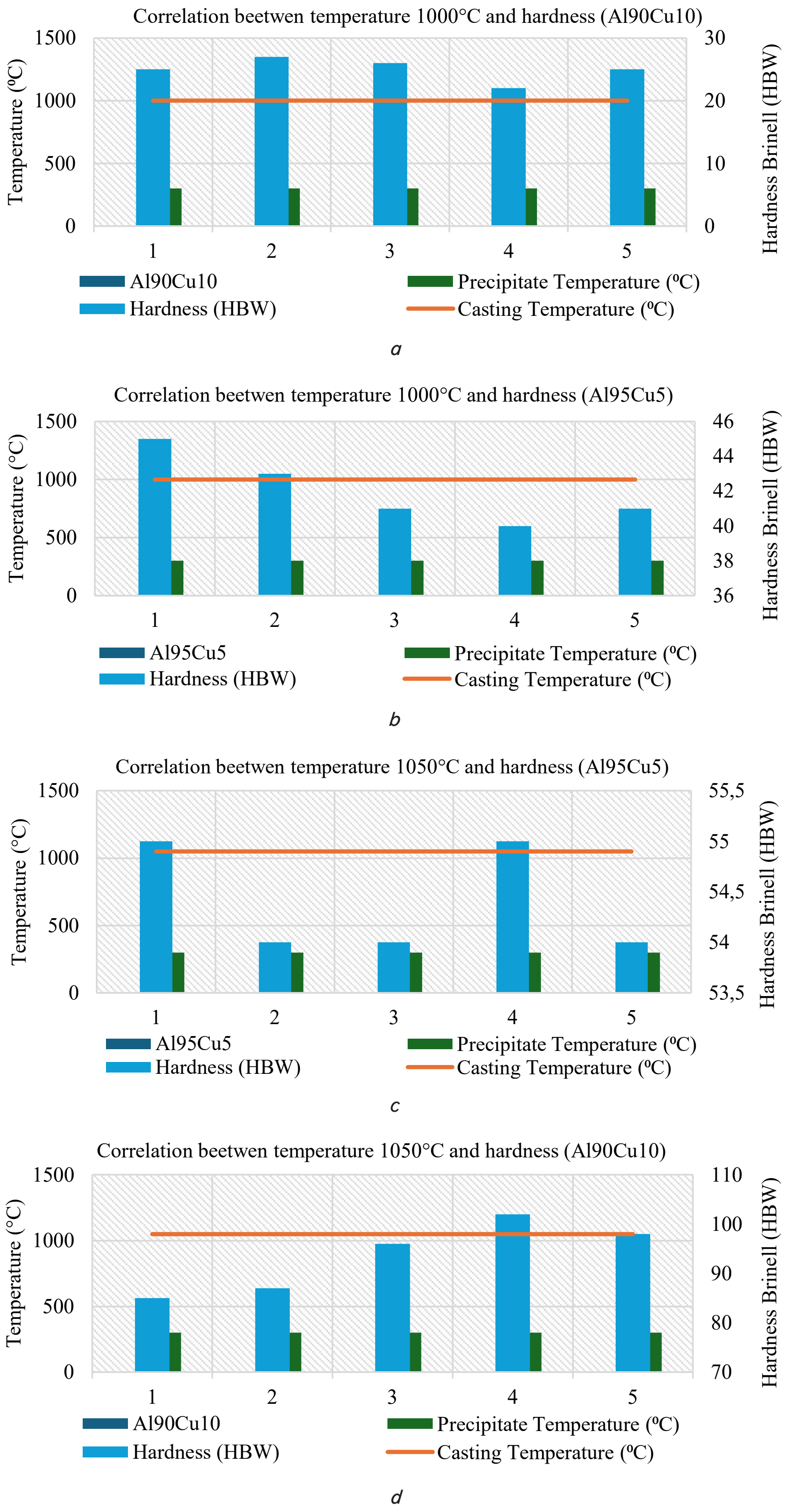


Fig. 6. The relationship between the setting temperature and the hardness level:
a – Al90Cu10 alloy, temperature 1000°C;
b – Al95Cu5 alloy, temperature 1000°C;
c – Al95Cu5, temperature 1050°C; *d* – Al90Cu10, temperature 1050°C

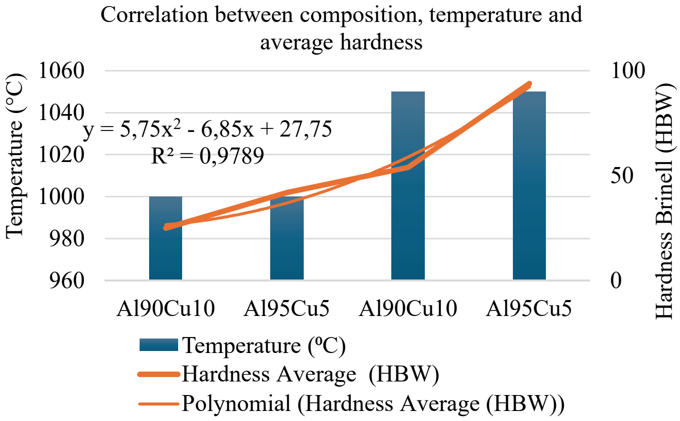


Fig. 7. Polynomial regression of average hardness

6. Discussion of manufacturing process and mechanical properties

The results of this study show that recycling aluminum with a copper belt fabricated by a melting process below the melting point of the copper element can dissolve the copper and increase hardness. The data in Table 3 show that the Al90Cu10 alloy has the least amount of slag melted at 1050°C. According to the right alloy composition in AL90Cu10, thermal energy efficiency can give the alloy a more homogeneous finish. The simulation results presented in Fig. 2, 3 indicate that precipitation occurs at 300°C. The increase in precipitation volume in the Al2Cu matrix affects hardness, as shown in Table 4; the aging process and diffusion are decisive in sediment formation.

The microstructure images of the Al and AlCu phases in Fig. 4 are evenly distributed and bounded by very clear granules; the finer, more evenly grained microstructures are affected by the composition of the dominant 10% Cu variation and by the 60-second cooling process. Statistical analysis showed in Fig. 7 that the determination coefficient (R2) of 0.9789 indicates a strong relationship among melting temperature, alloy composition, and AlCu alloy hardness. Analysis of the composition of aluminum and copper matrices has not been carried out in this study; however, using microstructural testing methods and thermal simulations, phase diagrams can be generated to support the use of recycled materials and energy savings in the metal casting industry [17, 18].

As described in Table 4, the increase in the hardness of recycled aluminum can be achieved through the addition of copper powder variants, control of melting temperatures below the melting point, and precipitation mechanisms. Temperature control can increase the yield strength of cast products, such as brass, and the addition of nickel can affect the alloy's hardness and material characteristics [19–21]. The Al90Cu10 alloy melted at 1050°C has a hardness of 94 HBW, compared to the alloy melted at 1000°C, which has a hardness of 25 HBW. This suggests that higher temperatures produce greater hardness.

Engineering components that require a higher degree of hardness and wear resistance, such as lightweight automotive components, simple molded components, bearing housings, and mount components, can use recycled Al-Cu alloy results with a precipitation mechanism for reinforcement. Temperature control and aging treatment can be applied in laboratory and industrial-scale casting processes. Support for the development of environmentally friendly materials, energy savings in smelting, and reductions in primary raw material consumption are outputs of materials engineering. The use of recycled aluminum with Cu powder can increase hardness through a precipitation mechanism.

The uniqueness of this study is that it reuses waste aluminum to produce an environmentally friendly, energy-efficient material with excellent strength, compared to new materials produced by mining and refining processes, which incur very high costs. The study is unique in that it explores recycled aluminum and its melting mechanisms under melting point and precipitation control. The focus of previous research was on the precipitation mechanism of primary materials and actual melting temperatures. Using recycled aluminum material lowers the melting temperature, providing good economic value and optimal hardness. Compared with previous research, there has been an increase in hardness and a decrease in energy consumption, supporting sustainable manufacturing.

A limitation of this study is that it does not test the final alloy composition or the slag-casting results to determine the final diffusion process outcomes that affect the alloy and slag compositions in the product. The need for reinforcing materials, such as powdered copper or nanoscale materials, and for other tests, in addition to violence, which are difficult to find on the market, presents the potential for materials engineering innovation in future research.

The disadvantage of this study is that the melting point may decrease during the manufacturing or smelting process, from a maximum of 1050°C to about 970°C, so that further experimental work can be carried out to test the homogeneity of aluminum and copper alloys, or other alloys containing copper. Another disadvantage is the potential for uneven Cu distribution during manual stirring, as well as increased oxidation and slag formation, which can worsen at higher melting temperatures. The precipitation mechanism uses only one temperature, so the optimization process remains limited. By using an automatic mixer and precise chemical composition testing for more in-depth analysis.

Future study will use nanoscale reinforcing materials to improve the mechanical properties of recycled alloys such as Ni and Mg. Thermodynamic simulations and further phase analysis will clarify the mechanisms of diffusion and precipitation. Detailed testing using SEM-EDS, XRD, and TEM analyses will offer alternative explanations for each defined variation. Maintaining homogeneity in recycled alloys, achieving stable temperatures, and determining optimal aging temperatures remain key research challenges.

7. Conclusions

1. The results of this study show that the addition of copper powder worth 5% and 10% can be combined with recycled aluminum with a melting process at temperatures of 1000°C and 1050°C, which is still carried by the melting point value of copper, which is at 1085°C. This result reinforces that the formation of the Al-Cu alloy matrix can occur from the diffusion mechanism process by partially melting copper. This is different from some previous studies that still use conventional smelting methods with conditions exceeding or approaching the melting point of the alloy. The approach

in this study has the potential to reduce energy consumption and support the use of recycled materials.

2. The results of observations on the microstructure explain that the Al90Cu10 alloy dominates in the Al matrix by being evenly distributed in the Al_2Cu phase and in the grain boundary area. The increase in temperature in the smelting process and aging treatment at 300°C makes the distribution of Al_2Cu alloy relatively even when precipitation occurs. The formation of microstructures in recycled aluminum-based Al-Cu alloys processed through a combination of melting processes at low temperatures and precipitation reinforcement is a scientific contribution of the results of this study.

3. The addition of Cu composition to recycled aluminum smelting proves that there is a significant effect on the hardness level of the alloy. The highest level of alloy hardness is found by alloy Al90Cu1, which is melted at a temperature of 1050°C and aged at a temperature of 300°C, resulting in an average of about 94 HBW. The formation of Al_2Cu precipitates that inhibit the movement of dislocations in the Al-Cu alloy is related to the increase in hardness. When compared to smelting with a temperature of 1000°C and a 5% Cu filling composition, resulting in a lower hardness level of about 25 HBW, this shows that the strengthening occurs due to higher temperatures and the addition of greater Cu content. Hence, this study answers the problem that the mechanical properties of recycled aluminum materials increase with an environmentally friendly and energy-efficient approach.

Conflict of interest

All authors declare that we have no conflicts of interest related to this study, whether financial, authorship, or otherwise that could affect the study and results presented in this paper.

Financing

This study was conducted with financial support from the Institute for Research and Community Service, Darma Persada University, Indonesia.

Data availability

Data will be available upon reasonable request.

Use of artificial intelligence

The authors assert that we do not use artificial intelligence technology in the creation of scientific papers.

Authors' contributions

Erwin: Conceptualization, Methodology, Writing – review & editing; **Juan Pratama**: Supervision, Writing – review & editing, Funding acquisition; **Didik Sugiyanto**: Formal analysis, Validation, Project administration; **Yefri Chan**: Resources, Investigation, Validation; **Trisna Ardi Wiradinata**: Data Curation, Resources, Writing – review & editing; **M. Arik Febrian**: Data Curation, Resources, Writing – original draft; **Dien Alma Ariz:** Visualization, Resources, Writing – original draft.

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