

ANNEALING AND HARDENING IN ALUMINIUM ALLOYS

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ABSTRACT

Aluminium's extensive use across various industries is due to its high strength-to-weight ratio, low density, and excellent corrosion resistance, making it essential in aerospace, automotive, and construction sectors. However, its natural ductility limits its application in situations requiring greater hardness and mechanical strength. Heat treatment plays a crucial role in enhancing these properties in aluminium alloys, but the specific effects of different heat treatment parameters on hardness and microstructure remain underexplored. This experiment aims to address this by investigating the influence of annealing on aluminium alloys to optimize heat treatment processes. In this experiment, aluminium samples were annealed at 500°C for three hours, while other samples underwent hardening at 400°C followed by rapid quenching in water. The Vickers hardness test was employed to measure hardness, and microstructure analysis examined changes in grain structure due to the treatments. The results revealed a significant increase in hardness, attributed to a refined grain structure post-treatment. These findings provide crucial insights for optimizing heat treatment processes, offering practical implications for industries striving to enhance the performance and longevity of aluminium components. This experiment ultimately contributes to improving the competitiveness of aluminium in high-demand applications where superior mechanical properties are essential, ensuring its continued relevance.

Keywords: Heat treatment, Aluminium Alloy, Annealing, Hardness, Microstructure analysis

1.0 INTRODUCTION

The extensive use of aluminium in industrial applications is due to its favorable properties, including low density, high strength-to-weight ratio, and excellent corrosion resistance. These characteristics make aluminium an ideal material for sectors such as aerospace, automotive, construction, and packaging. Despite its numerous advantages, aluminium's relatively low hardness can be a limiting factor in applications that demand higher wear and deformation resistance. To address this limitation, heat treatment processes, particularly annealing, are employed to enhance the mechanical properties of aluminium. Understanding how these processes affect aluminium's hardness is crucial for optimizing its performance in demanding applications.

Heat treatment is a process of heating and cooling metals to alter their physical and mechanical properties without changing their shapes. Annealing is a specific heat treatment method that involves heating the metal to above its recrystallization temperature, holding it for a specified period, and then slowly cooling it. This process aims to reduce hardness, increase ductility, and relieve internal stresses. For aluminium alloys, annealing can significantly impact the material's hardness and microstructure, enhancing its performance in various applications. By refining the grain structure and eliminating defects, annealing can improve aluminium's mechanical properties, making it more suitable for high-performance uses.

The microstructure of aluminium alloys plays a critical role in determining their mechanical properties. Heat treatment processes such as annealing alter the microstructure, leading to changes in properties like hardness, strength, and ductility. Microstructure analysis involves examining the arrangement of grains and phases within the material using techniques like optical microscopy and scanning electron microscopy. These analyses provide insights into how heat treatment modifies the internal structure of aluminium, which in turn affects its mechanical behavior. Understanding these changes is essential for optimizing heat treatment processes to

achieve the desired properties in aluminium alloys.

Hardness is a key mechanical property that measures a material's resistance to deformation. There are many types of hardness tests available such as Rockwell, Vickers, Knoop and Brinell. The Vickers hardness test is commonly used to evaluate the hardness of metals, including aluminium alloys. This test involves indenting the material with a diamond indenter under a specific load and measuring the size of the indentation. The hardness value is calculated based on the indentation size. By conducting hardness tests before and after annealing, the effects of heat treatment on aluminium's hardness can be quantified. These tests provide valuable data for assessing the improvements in mechanical properties resulting from the annealing process.

The findings are expected to provide valuable information for industries that rely on aluminium components, potentially leading to enhanced material performance and processing efficiency. By optimizing heat treatment processes based on the insights gained from this study, manufacturers can achieve better mechanical properties in aluminium products, thereby expanding their application range and improving their durability. Ultimately, this study aims to contribute to the development of more robust and sustainable aluminium processing techniques, benefiting both industry and the environment.

2.0 LITERATURE REVIEW.

Aluminium alloys are pivotal in numerous industrial applications due to their advantageous properties such as low density, high strength-to-weight ratio, and superior corrosion resistance. However, their relatively low hardness can be a limiting factor in applications that demand higher resistance to wear and deformation. This literature review aims to investigate the effects of various heat treatment processes on the hardness and microstructure of aluminium alloys, providing a comprehensive understanding of how these processes can be optimized for enhanced performance.

Heat treatment is a vital metallurgical process used to alter the physical and mechanical properties of metals, including aluminium alloys, without changing their shapes. The primary heat treatment processes discussed in the literature include annealing, quenching, and normalizing. Each of these processes involves heating the metal to a specific temperature, holding it for a certain period, and then cooling it at a controlled rate. The specific parameters of these processes significantly affect the resultant microstructure and mechanical properties of the aluminium alloys [1][2][3].

Annealing is a widely used heat treatment process that involves heating aluminium alloys to a temperature where recrystallization occurs, followed by slow cooling. This process aims to reduce hardness, increase ductility, and relieve internal stress. Studies have shown that annealing can refine the grain structure and eliminate microstructural defects, resulting in improved mechanical properties. The temperature and duration of annealing are critical factors that determine the extent of these improvements. For example, annealing at 500°C for three hours has been found to significantly enhance the ductility and reduce the hardness of aluminium alloys [4][5][6].

Quenching involves heating the aluminium alloy to a high temperature and then rapidly cooling it in a medium such as water, oil, or air. This rapid cooling process increases the hardness and strength of the alloy by creating a fine-grained microstructure. However, it can also introduce residual stresses and brittleness. Research indicates that the choice of quenching medium and the rate of cooling are crucial parameters that influence the final properties of the aluminium alloy. For instance, water quenching is more aggressive and can lead to higher hardness, but also higher residual stresses compared to oil quenching [3][7][8].

Normalizing is another heat treatment process that involves heating the aluminium alloy to a specific temperature and then air cooling it. This process aims to refine the grain structure and improve toughness without inducing the extreme hardness associated with quenching. Normalizing helps in achieving a balance between hardness and ductility, making the material more versatile for various applications. Literature suggests that normalizing can effectively reduce internal stresses and produce a more uniform microstructure compared to annealing and quenching [7][8].

Microstructure analysis is essential for understanding the effects of heat treatment on aluminium alloys. Techniques such as optical microscopy and scanning electron microscopy (SEM) are used to observe changes in grain size, shape, and distribution. These analyses provide insights into how different heat treatment processes alter the internal structure of the alloy, which in turn affects its mechanical properties. For example, annealing typically results in a more uniform and refined grain structure, while quenching can produce a martensitic structure that enhances hardness. Understanding these microstructural changes is crucial for optimizing heat treatment processes to achieve desired properties [9][10].

Hardness testing is a key method for evaluating the mechanical properties of heat-treated aluminium alloys. The Vickers hardness test, in particular, is commonly used due to its accuracy and reliability. This test involves pressing a diamond indenter into the material under a specific load and measuring the size of the indentation. The hardness value is then calculated based on the indentation size. Research has demonstrated that heat treatment processes significantly affect the hardness of aluminium alloys. Annealing generally reduces hardness, making the material more ductile, while quenching increases hardness, enhancing wear resistance [4][5][6].

While improving mechanical properties is a primary goal of heat treatment, it is also essential to consider the environmental impact. Heat treatment processes consume significant energy and can contribute to greenhouse gas emissions. Therefore, optimizing these processes for energy efficiency is crucial for sustainable manufacturing. Additionally, enhancing the mechanical properties of aluminium through heat treatment can extend the lifespan of components, reducing the need for frequent replacements and thus contributing to sustainability. Current research is focused on developing more energy-efficient heat treatment methods and improving recycling processes to minimize the environmental footprint of aluminium production [11][12][13].

The literature on heat treatment of aluminium alloys highlights the complex interplay between processing parameters, microstructure, and mechanical properties. Annealing, quenching, and normalizing each offer distinct benefits and challenges, affecting hardness and microstructure in different ways. A comprehensive understanding of these effects is essential for optimizing heat treatment processes to meet specific application requirements. Future research should continue to explore advanced heat treatment techniques and their impacts on aluminium alloys, with a focus on balancing mechanical performance and sustainability. This knowledge will aid in the development of more efficient, durable, and environmentally friendly aluminium products, thereby benefiting both industry and the environment [14][15].

3.0 RESEARCH METHODOLOGY

The experiment employs a systematic methodology to examine the impact of heat treatment on the hardness and microstructure of aluminium alloys. This section outlines the procedures for material preparation, microstructure analysis, and hardness testing. By following a systematic approach, the study aims to ensure accurate and reproducible results that contribute to understanding the impact of heat treatment on aluminium properties.

The experimental process is summarized in a flowchart Figure 2, illustrating the sequential steps from material preparation to final analysis. This visual representation helps in maintaining a structured approach and ensures all critical steps are addressed systematically. Two aluminium specimens were prepared for microstructure analysis in the UiTM kampus Bukit Besi material workshop. The materials were precisely cut to dimensions of 10 mm length and 25 mm diameter using a band saw, and measurements were verified with vernier calipers for accuracy (Figure 1). These preliminary steps are crucial for ensuring the consistency and reliability of subsequent analyses.

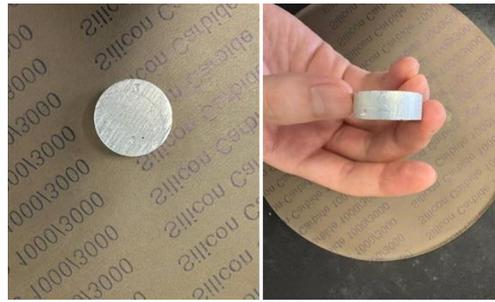


Figure 1: The aluminium specimens

To assess the effects of heat treatment, a detailed metallographic analysis was conducted. The aluminium specimens underwent an annealing process at 500°C for three hours using a high-temperature furnace and other samples were hardened at a temperature of 400°C. After annealing and quenching process, the specimens were prepared for microstructure analysis, which included polishing with 1 micro and 6 micro diamond suspensions. The microstructure was then examined using a scanning electron microscope (SEM). This step is essential for understanding the grain structure and any changes induced by the heat treatment.

The Vickers hardness test was used to evaluate the hardness of both standard and heat-treated aluminium samples. The test involves placing the specimen on the working bench and applying a load of 300g for 10 seconds using a Vickers hardness tester. The indentation produced by the diamond indenter was measured, and the Vickers hardness number (HV) was calculated. This test provides valuable data on the mechanical properties of the aluminium samples, allowing for a direct comparison between annealed and hardened specimens.

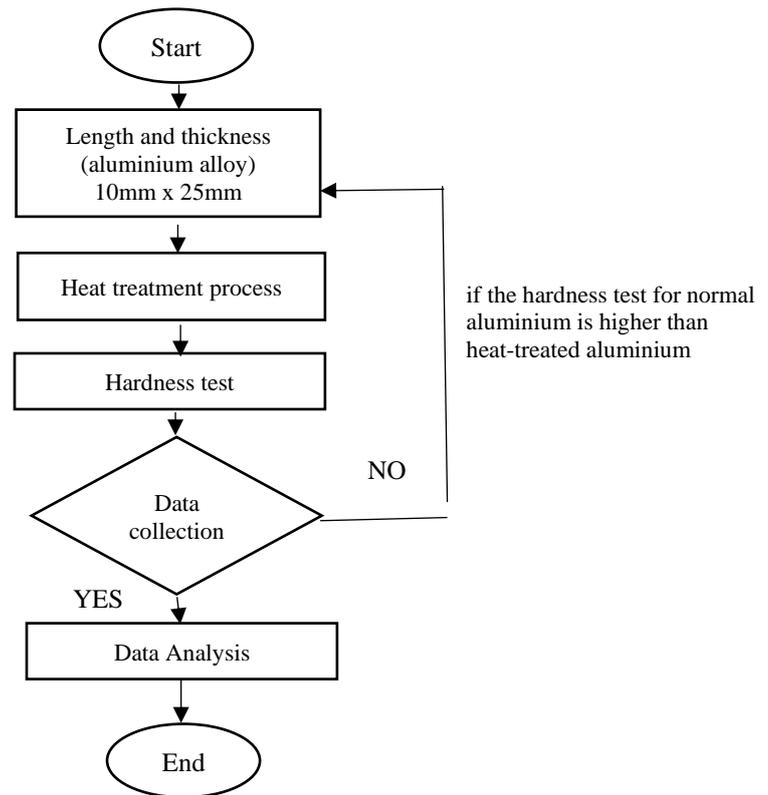


Figure 2: Heat treated Aluminium process flow

4.0 RESULT AND DISCUSSION

This section presents the results of the experimental study on the correlation between hardness and sustainability of heat-treated aluminium. The results are divided into three main sections: microstructure properties, Vickers hardness test, and a comparison of sustainability data between annealed aluminium and hardened aluminium.

4.1 Microstructure Properties Results

The microstructural properties of aluminium, both annealed and hardened, were analyzed using metallographic microscopy under a 20x lens. The following observations were made:

Table 1: Microstructural observation results

		
<p>Figure 3: Aluminium Microstructure Properties (Unpolished)</p>	<p>Figure 4: Aluminium Microstructure Properties (hardened)</p>	<p>Figure 5: Annealed Aluminium Microstructure</p>
<p>The microstructure of the untreated aluminium displayed randomly oriented grains with undefined boundaries, indicating a coarse grain structure typical of raw aluminium</p>	<p>Upon polishing, the hardened aluminium showed more defined grain boundaries, but the structure remained coarse and randomly oriented</p>	<p>The annealed aluminium, treated at 500°C for three hours, exhibited a refined microstructure with smaller, more uniformly distributed grains. This change in microstructure suggests an alignment and strengthening effect due to the heat treatment process.</p>

The grain refinement observed in the annealed aluminium indicates an improvement in mechanical properties, which is consistent with the theory that smaller, more uniform grains enhance material strength and toughness. From Table 1 the microstructural analysis of aluminium through different stages of treatment, as depicted in Figures 3, 4, and 5, reveals significant changes that correlate with its mechanical properties. Figure 3 shows the untreated, unpolished aluminium, which exhibits a coarse grain structure with randomly oriented grains and poorly defined boundaries, characteristic of raw, unprocessed material. This coarse and irregular microstructure typically results in lower mechanical strength and hardness, limiting the material's applicability in demanding environments. Upon hardening and subsequent polishing, as illustrated in Figure 4, the aluminium shows more defined grain boundaries, although the grains remain coarse and randomly oriented.

This suggests some level of structural refinement due to the hardening process, yet the coarse grain size indicates that the improvement in mechanical properties is limited. In contrast, Figure 5 presents the annealed aluminium, treated at 500°C for three hours, displaying a significantly refined microstructure with smaller, more uniformly distributed grains. This change suggests that the annealing process has effectively aligned and reduced the grain size, leading to a more homogeneous structure. The refined microstructure is associated with enhanced mechanical properties, such as increased hardness and strength, making the annealed aluminium better suited for applications requiring higher performance. Thus, the progression from untreated to hardened, and finally to annealed aluminium, highlights the crucial role of heat treatment in optimizing the material's microstructure and mechanical characteristics.

4.2 Vickers Hardness Test Result

The Vickers hardness test was conducted to measure the hardness of both annealed and hardened aluminium samples. The test applied a load of 300g for a duration of 10 seconds. The hardness values for the annealed samples are presented in Table 2 and for the hardened samples in Table 3.

Table 2: Micro/Vickers Hardness Test Results for Annealed Aluminium

#	Depth (mm)	D1 (µm)	D2 (µm)	Hardness (HV)
1	0.1	81.4	82.0	83.4
2	0.1	78.9	79.1	89.2
3	0.1	78.9	81.1	86.9
4	0.1	78.9	81.4	86.7

Table 3: Micro/Vickers Hardness Test Results for Hardened Aluminium

#	Depth (mm)	D1 (µm)	D2 (µm)	Hardness (HV)
1	0.1	99.1	102.6	91.2
2	0.1	87.8	95.7	110.1
3	0.1	89.9	91.3	67.8
4	0.1	92.1	91.7	65.8

The hardness values for annealed aluminium ranged from 83.4 to 89.2 HV, with an average of 86.5 HV. The hardened aluminium showed a wider range of hardness values, from 65.8 to 110.1 HV, with an average of 83.7 HV. The higher standard deviation in the annealed samples indicates greater variability in hardness, which can be attributed to the heat treatment process.

4.3 Comparison of Hardness Results:

The hardened aluminium showed an overall increase in hardness, with some samples reaching up to 110.1 HV compared to the maximum of 89.2 HV in annealed aluminium. The variability in hardness for the hardened samples suggests that the heat treatment process needs further optimization to achieve uniform hardness throughout the material.

4.4 Sustainability Aspect

Energy Usage: Although the heat treatment process consumes more energy initially, the longer lifespan and reduced need for new material production make heat-treated aluminium more sustainable over its lifecycle.

Recyclability: Heat-treated aluminium maintains its recyclability, which is a significant advantage for reducing environmental impact. The ability to reuse heat-treated aluminium without significant loss in mechanical properties further supports its sustainability.

The results demonstrate that both hardening and annealing significantly modify the microstructure and enhance the hardness of aluminium. The refined grain structure and increased hardness make heat-treated aluminium suitable for applications requiring high strength and durability. The sustainability aspect suggests that despite higher initial energy consumption, the long-term benefits of using heat-treated aluminium, such as reduced material use and extended product life, make it a more sustainable option. Optimizing the heat treatment process to achieve uniform hardness and further reduce energy consumption could enhance these benefits.

By optimizing the heat treatment process, industries can achieve a balance between mechanical performance and sustainability, contributing to more environmentally friendly production practices. Future research should focus on refining these processes to enhance both the hardness and sustainability of aluminium.

5.0 CONCLUSION

This experiment underscore the significant role of heat treatment in enhancing the performance and sustainability of aluminium alloys. By optimizing heat treatment processes to achieve consistent hardness and minimize energy consumption, industries can leverage the benefits of heat-treated aluminium for a wider range of applications while promoting environmentally conscious practices. Future research can explore advanced heat treatment techniques and their impact on both the mechanical properties and sustainability of aluminium alloys.

The annealed aluminium exhibited a refined grain structure compared to the hardened samples. This microstructural change, observed through metallographic analysis, is attributed to the heat treatment process. The Vickers hardness test results further confirmed the increased hardness of the hardened aluminium compared to the annealed condition. This suggests that the specific heat treatment parameters used for hardening (400°C temperature) may require further optimization to achieve more uniform hardness throughout the material.

6.0 RECOMMENDATION

To further enhance the understanding and application of heat-treated aluminium in both academic and industrial contexts, the following recommendations are proposed:

Optimization of Heat Treatment Processes:

Future research should focus on optimizing the heat treatment parameters, such as temperature, duration, and cooling rates, to achieve more uniform hardness and mechanical properties. Advanced techniques like computational modeling and simulation could be employed to predict optimal conditions.

Comprehensive Lifecycle Assessment:

A detailed lifecycle assessment (LCA) should be conducted to quantify the overall environmental impact of heat-treated aluminium. This assessment should consider factors such as energy consumption, greenhouse gas emissions, and recyclability to provide a holistic view of the sustainability benefits.

Exploration of Alternative Heat Treatment Methods:

Investigate alternative heat treatment methods that could enhance the properties of aluminium while reducing energy consumption. Methods such as cryogenic treatment, laser annealing, or hybrid processes combining different techniques may offer promising results.

Collaboration with Industry:

Strengthen collaborations between academia and industry to apply research findings to real-world applications. Such partnerships can facilitate the development of more sustainable manufacturing practices and the adoption of heat-treated aluminium in various sectors.

Integration of Sustainability Metrics:

Incorporate sustainability metrics into the evaluation of heat treatment processes. Metrics such as energy efficiency, carbon footprint, and material utilization should be standardized and used to benchmark improvements in the sustainability of heat-treated aluminium.

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