Volume 4 Number 2 (2026)
July-December 2026
Page: 4285-4296

Journal of Creative Power and Ambition (JCPA)
https://edujavare.com/index.php/jcpa
E-ISSN: 3031-4054
DOI: 10.70610/jcpa.2256

Analysis of the Effect of Annealing Heat Treatment on the Mechanical Properties of Aluminium Alloy 6061

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Article history Submitted: 2026/09/08; Revised: 2026/10/11; Accepted: 2026/11/12

Abstract

This study investigates the effect of annealing temperature on the mechanical properties and microstructural characteristics of aluminium alloy 6061. The research used a quantitative laboratory experimental approach with annealing temperatures of 450°C, 495°C, and 550°C. The specimens were held for 1 h at each temperature and then cooled slowly inside the furnace. Tensile testing was conducted using a Universal Testing Machine, hardness was evaluated using the Vickers method, and microstructure was observed using a metallographic microscope at 100× and 200× magnification. Three specimens were used for each temperature. The average tensile strength decreased from 130.51 MPa at 450°C to 126.06 MPa at 495°C and 117.45 MPa at 550°C. Average hardness also decreased from 37.7 VHN to 35.8 VHN and 35.1 VHN, respectively. Elongation showed a non-linear response, decreasing from 19.67% at 450°C to 18.00% at 495°C and increasing again to 19.67% at 550°C. Microstructural observations showed qualitative changes in the appearance, distribution, and uniformity of the observed structure with increasing annealing temperature. Because grain size was not measured quantitatively, the microstructural interpretation was limited to visual comparison. Overall, 450°C produced the highest combination of tensile strength and hardness among the investigated conditions.

Keywords Aluminium Alloy 6061, Annealing, Tensile Strength, Hardness, And Microstructure

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INTRODUCTION

Aluminium alloys have become essential engineering materials in various industrial sectors, particularly aerospace, automotive, construction, marine, and manufacturing industries. Their widespread application is primarily attributed to their relatively low density, favorable strength-to-weight ratio, corrosion resistance, machinability, and good formability. These characteristics allow aluminium alloys to be used in components that require lightweight construction without sacrificing essential mechanical performance. Among the different aluminium alloy series, aluminium alloy 6061 is widely recognized as a versatile Al-Mg-Si alloy because of

its combination of mechanical strength, corrosion resistance, weldability, and processing characteristics (You et al., 2024). These properties make it suitable for structural components and engineering applications where material efficiency and mechanical reliability are important considerations.

Despite these advantages, the mechanical properties of aluminium alloys are not determined solely by their chemical composition. Their performance is also strongly influenced by manufacturing processes, previous deformation, thermal exposure, and microstructural conditions. Changes in thermal history can modify the internal structure of a material and consequently affect its strength, hardness, ductility, and resistance to deformation. In aluminium alloys, the relationship between processing conditions, microstructure, and mechanical properties is particularly important because different heat-treatment procedures can produce different material responses (Hirsch, 2016). Therefore, controlling the heat-treatment process is necessary to obtain mechanical properties that correspond to the requirements of specific engineering applications.

Annealing is one of the heat-treatment methods commonly applied to metallic materials to modify their internal structure and mechanical behavior. Generally, the process involves heating a material to a predetermined temperature, maintaining it at that temperature for a specified period, and subsequently allowing it to cool under controlled conditions. In aluminium alloys, annealing can promote recovery, recrystallization, and grain growth, depending on the initial material condition and the applied temperature and holding time. Recovery involves the rearrangement and reduction of internal defects, while recrystallization involves the formation of new grains with relatively low internal strain. Further exposure to elevated temperatures may encourage grain coarsening, which can influence the strength and ductility of the material (Dorward, 2018; Hirsch, 2016). Consequently, annealing temperature is an important parameter in determining the final microstructure and mechanical characteristics of aluminium alloys.

Previous investigations have demonstrated that heat-treatment conditions can significantly influence the mechanical properties of aluminium alloy 6061. Ridhwan et al. (2014), for example, reported that different cooling conditions and heat-treatment procedures produced substantial variations in the microstructure and mechanical performance of 6061 aluminium alloy. Their findings indicated that furnace cooling after annealing could result in a softer material condition, whereas other heat-treatment routes could improve strength through different microstructural mechanisms. Similarly, Bin et al. (2024) examined the influence of

heat-treatment temperature and duration on the mechanical characteristics and microstructure of AA6061. Their study highlighted the importance of controlling heating conditions because variations in temperature can produce different combinations of tensile strength, hardness, and elongation. These findings suggest that the mechanical response of aluminium alloy 6061 should be evaluated by considering the relationship between heat-treatment parameters and microstructural development.

The mechanical properties commonly used to evaluate the effectiveness of annealing include tensile strength, hardness, and elongation. Tensile strength indicates the maximum stress that a material can withstand before failure, while hardness represents its resistance to localized plastic deformation. Elongation provides information about the material's capacity to undergo deformation before fracture and is commonly used as an indicator of ductility. These parameters do not necessarily change in the same direction following heat treatment. A reduction in tensile strength and hardness may indicate material softening, while changes in elongation may reflect differences in its capacity for plastic deformation. Research on aluminium alloys has shown that heat-treatment conditions can produce complex relationships between strength, ductility, and microstructural characteristics (Jia et al., 2025; Ridhwan et al., 2014). Therefore, evaluating only one mechanical parameter may provide an incomplete understanding of the material's response to annealing.

Although previous studies have discussed the effects of heat treatment on aluminium alloys, further investigation is relevant to understanding the response of aluminium alloy 6061 under different annealing temperatures and consistent holding and cooling conditions. In particular, comparing several temperature levels while maintaining the holding time and cooling procedure provides an opportunity to examine how temperature variations are associated with changes in mechanical properties and observable microstructural characteristics. Such an investigation is important because the most favorable annealing condition cannot be determined simply by assuming that a higher temperature will produce better mechanical performance. Instead, the selection should be based on the combined evaluation of tensile strength, hardness, elongation, and microstructural observations.

Based on this consideration, the present study investigates the effect of annealing temperatures of 450°C, 495°C, and 550°C on the mechanical properties and microstructure of aluminium alloy 6061. Each specimen is subjected to a holding time of one hour, followed by slow cooling inside the furnace. The mechanical properties are evaluated through tensile testing and Vickers hardness testing, while

microstructural characteristics are examined using metallographic observations at 100× and 200× magnification. The study aims to identify the trends in tensile strength, hardness, and elongation resulting from different annealing temperatures and to compare the visible microstructural characteristics of the treated specimens. Through this approach, the research is expected to provide a clearer understanding of the relationship between annealing temperature and the mechanical behavior of aluminium alloy 6061, as well as identify the most favorable condition among the investigated temperatures based on the measured mechanical properties.

METHODS

This study employed a quantitative laboratory experimental approach to investigate the effect of annealing temperature on the mechanical properties and microstructural characteristics of aluminium alloy 6061. An experimental design was selected because it allows the influence of a controlled treatment variable on material properties to be examined under specified laboratory conditions. The independent variable was annealing temperature, which consisted of three experimental levels: 450°C, 495°C, and 550°C. The dependent variables included tensile strength, hardness, elongation, and microstructural characteristics. To maintain consistency across the experimental conditions, the holding time was fixed at one hour, and all specimens underwent furnace cooling after the annealing process. Aluminium alloy 6061 was selected as the experimental material because of its established engineering applications and its sensitivity to thermal processing conditions (You et al., 2024).

A total of nine specimens were prepared for the mechanical tests, with three specimens assigned to each annealing temperature. This arrangement provided three experimental observations for every temperature condition and enabled the calculation of average mechanical-property values. Before heat treatment, the specimens were prepared and assigned identification codes according to their respective temperature groups. Specimen identification was intended to facilitate the organization of experimental data and ensure that the results obtained from tensile and hardness testing could be associated with the corresponding annealing conditions. The use of consistent specimen preparation and treatment procedures was important to minimize procedural differences among the experimental groups.

The heat-treatment process was conducted using a furnace capable of reaching the three predetermined annealing temperatures. Each specimen was placed inside the furnace and heated until the assigned temperature was reached. The specimens were then maintained at the target temperature for one hour to provide a consistent holding period across all experimental groups. The three temperature conditions

were 450°C, 495°C, and 550°C, respectively. After the holding period had been completed, the specimens were not immediately removed from the furnace. Instead, they remained inside the furnace and were allowed to cool gradually to room temperature through furnace cooling.

The same heating, holding, and cooling procedures were applied to all specimens to maintain consistency in the experimental treatment. The use of different annealing temperatures under an identical holding time and cooling procedure enabled the study to focus on the relationship between temperature variation and the resulting material properties. Heat treatment can influence the internal structure of aluminium alloys through processes such as recovery, recrystallization, and grain growth. The extent of these changes depends on the temperature and duration of thermal exposure, as well as the initial condition of the material (Hirsch, 2016). Therefore, maintaining consistent treatment conditions was essential for comparing the mechanical responses of the three specimen groups.

Mechanical testing was conducted to evaluate the effects of annealing temperature on the strength, hardness, and ductility of aluminium alloy 6061. Tensile testing was performed using a Universal Testing Machine (UTM). The procedure followed the tensile-testing approach specified in ASTM E8/E8M, which provides standardized methods for determining the tensile properties of metallic materials, including tensile strength and elongation (ASTM International, 2025). The principal parameters recorded in this study were maximum tensile stress and elongation. Maximum tensile stress was used to evaluate the material's resistance to tensile loading, while elongation represented its deformation capacity before fracture. Three specimens were tested for each annealing temperature, and the resulting measurements were recorded for subsequent comparison.

Hardness testing was conducted using the Vickers hardness method. The results were expressed as Vickers Hardness Number (VHN), representing the material's resistance to localized indentation. The Vickers method is commonly used for evaluating hardness variations in metallic materials and provides a basis for comparing the mechanical response of specimens subjected to different processing conditions (ASTM International, 2022). In this study, hardness measurements were obtained from specimens treated at 450°C, 495°C, and 550°C. The resulting values were recorded and used to calculate the average hardness for each temperature group. The combination of tensile and hardness testing provided complementary information about changes in the mechanical performance of the annealed specimens.

Microstructural examination was performed to observe changes in the internal structure of aluminium alloy 6061 after annealing. The metallographic specimens were prepared through a sequence of cutting, mounting, grinding, polishing, and etching procedures. After mechanical surface preparation, the specimens were etched using Keller's reagent to reveal observable microstructural features. The prepared surfaces were subsequently examined using an optical metallographic microscope at magnifications of 100× and 200×. The same magnification levels were used for the different temperature conditions to support visual comparison of the observed structures.

The microstructural analysis focused on visible differences in the appearance, arrangement, distribution, and apparent uniformity of the structures observed in the micrographs. In particular, the observations were used to identify qualitative changes associated with increasing annealing temperature. However, this study did not include quantitative grain-size measurement. Consequently, the microstructural interpretation was restricted to visual comparison and was not used to establish numerical grain-size differences or definitive recrystallization mechanisms. This limitation was considered when relating the microstructural observations to the mechanical test results.

The experimental data were analyzed using descriptive quantitative analysis. For each annealing temperature, the individual tensile strength, hardness, and elongation measurements were organized according to their respective specimen groups. The arithmetic mean was then calculated from the three measurements obtained under each temperature condition. These average values were compared to identify changes in mechanical properties as the annealing temperature increased from 450°C to 550°C. The comparison focused on the direction and magnitude of changes in tensile strength, hardness, and elongation. Microstructural data were analyzed qualitatively by comparing the optical micrographs obtained at 100× and 200× magnification. The visual observations were considered alongside the mechanical test results to provide a broader interpretation of the material's response to annealing. No inferential statistical analysis or quantitative grain-size analysis was performed. Therefore, the findings were interpreted primarily through descriptive comparisons among the three experimental temperature conditions. This analytical approach was intended to identify the annealing condition that produced the most favorable combination of mechanical properties within the investigated temperature range.

FINDINGS AND DISCUSSION

Tensile Strength

The tensile-test results show a clear decrease in maximum tensile stress as the annealing temperature increased. At 450°C, the three specimens produced maximum tensile stresses of 132.55, 127.38, and 131.60 MPa. At 495°C, the values were 127.70, 125.85, and 124.63 MPa, while at 550°C the values were 116.70, 118.06, and 117.59 MPa.

Table 1. Average tensile strength of aluminium alloy 6061

Annealing temperature	Average tensile strength (MPa)
450°C	130.51
495°C	126.06
550°C	117.45

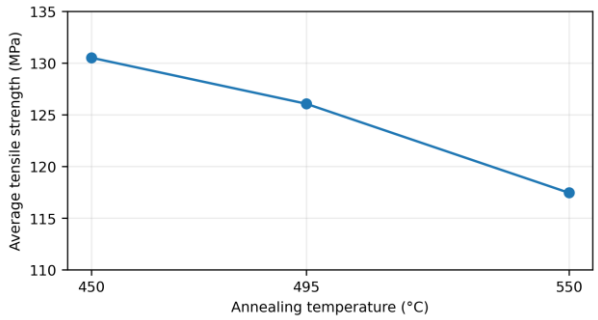


Figure 1. Effect of annealing temperature on average tensile strength

The average tensile strength decreased by 4.45 MPa when the temperature increased from 450°C to 495°C and by a further 8.61 MPa from 495°C to 550°C. Overall, the decrease from 450°C to 550°C was 13.06 MPa, or about 10.01%. The trend indicates that, under the conditions investigated, increasing annealing temperature was associated with reduced resistance to tensile loading. This behavior is consistent with the general role of annealing in reducing internal stress and promoting structural changes that can soften a previously worked material.

Hardness

Vickers hardness measurements also showed a decreasing trend with increasing annealing temperature. The 450°C specimens gave hardness values of 36.8, 38.9, and 37.3 VHN. At 495°C, the values were 35.3, 35.8, and 36.3 VHN, while the 550°C specimens produced 34.8, 35.8, and 34.8 VHN.

Table 2. Average Vickers hardness of aluminium alloy 6061

Annealing temperature	Average hardness (VHN)
450°C	37.7

495°C	35.8
550°C	35.1

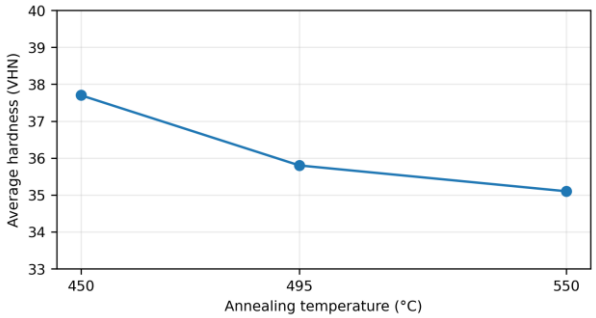


Figure 2. Effect of annealing temperature on average hardness

The average hardness decreased by 1.9 VHN between 450°C and 495°C and by 0.7 VHN between 495°C and 550°C. The total decrease from 450°C to 550°C was 2.6 VHN, equivalent to approximately 6.90%. The reduction in hardness followed the same direction as the tensile-strength decrease, indicating a tendency toward a softer material condition as the annealing temperature increased.

Elongation

Unlike tensile strength and hardness, elongation did not show a monotonic trend. The average elongation at 450°C was 19.67%, decreased to 18.00% at 495°C, and increased again to 19.67% at 550°C.

Table 3. Average elongation of aluminium alloy 6061

Annealing temperature	Average elongation (%)
450°C	19.67
495°C	18.00
550°C	19.67

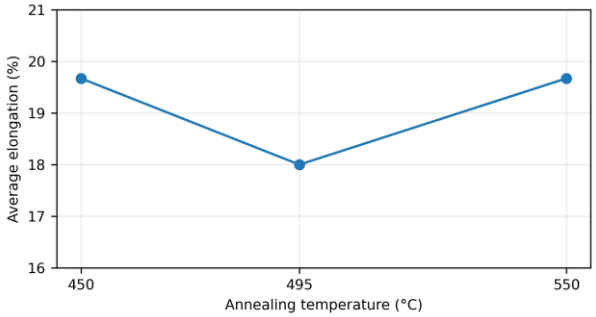


Figure 3. Effect of annealing temperature on average elongation

The change from 450°C to 495°C represents a decrease of 1.67 percentage points, whereas the change from 495°C to 550°C represents an increase of 1.67 percentage points. Therefore, within the tested range, annealing temperature did not produce a continuously increasing or decreasing elongation response.

Microstructural Observation

Microstructural observations were carried out at 100× and 200× magnification for the 450°C, 495°C, and 550°C conditions. The photographs were compared at the same magnification to evaluate visible differences in the shape, arrangement, distribution, and apparent uniformity of the observed structure.

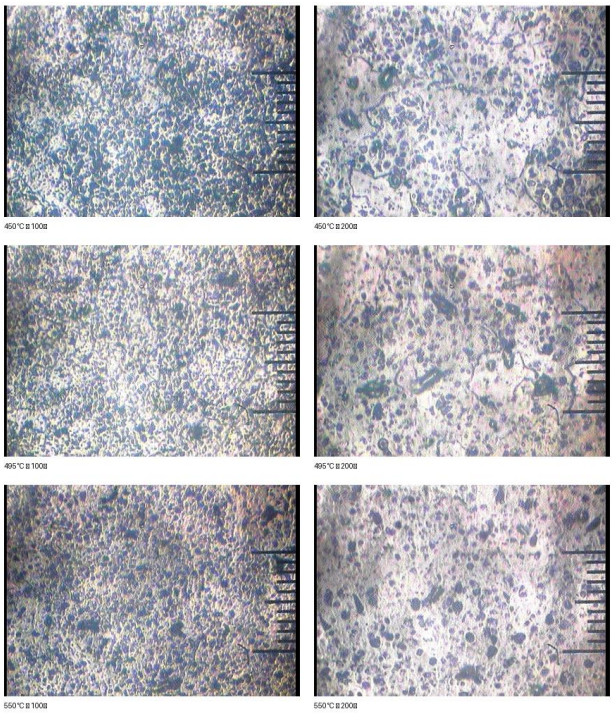


Figure 4. Microstructures after annealing at 450°C, 495°C, and 550°C at 100× and 200× magnification

The micrographs show qualitative changes in the appearance of the aluminium alloy structure as the annealing temperature increases. The thesis emphasizes that these observations are visual and do not provide a quantitative grain-size measurement. Consequently, the photographs are used to support the interpretation of mechanical-property trends rather than to assign a specific grain-size value or a definitive metallurgical mechanism without additional characterization (Q. Li et al, 2010). The increase in annealing temperature provides greater thermal energy for internal structural changes. In the present results, this change occurs together with decreasing tensile strength and hardness. Thus, the microstructural observations support the overall tendency toward softening as the annealing temperature rises (T. Hong et al, 2023)

Relationship between Microstructure and Mechanical Properties

The relationship between microstructure and mechanical properties can be seen from the parallel decrease in tensile strength and hardness (F. E. El Garchani et al, 2023). The highest average tensile strength and hardness were obtained at 450°C,

whereas the lowest values were obtained at 550°C [13]. This indicates that the internal structural condition produced by the different annealing temperatures is associated with changes in the ability of the material to resist tensile loading and indentation (M. N. Grażyna et al, 2021).

Elongation behaved differently, with the lowest average value at 495°C and a return to 19.67% at 550°C (I. El-Mahallawi et al, 2025). Therefore, the response of aluminium alloy to annealing cannot be represented by a single mechanical parameter. A complete interpretation requires tensile strength, hardness, elongation, and microstructural observations to be considered together (E. K. Kweitsu et al, 2024)

Comparison of Annealing Temperatures

Table 4. Summary of mechanical properties at each annealing temperature

Temperature	Tensile strength (MPa)	Hardness (VHN)	Elongation (%)
450°C	130.51	37.7	19.67
495°C	126.06	35.8	18.00
550°C	117.45	35.1	19.67

Considering tensile strength and hardness as the main selection parameters, 450°C can be regarded as the most favorable condition among the three investigated temperatures. It produced the highest average tensile strength (130.51 MPa) and the highest average hardness (37.7 VHN), while its average elongation was also 19.67%. The 550°C condition produced the lowest tensile strength and hardness, although its elongation returned to the same average value as 450°C (R. Lin et al, 2022).

CONCLUSION

Increasing the annealing temperature from 450°C to 550°C reduced the average tensile strength of aluminium alloy 6061 from 130.51 MPa to 117.45 MPa and reduced the average hardness from 37.7 VHN to 35.1 VHN.Elongation did not show a monotonic response. The average value decreased from 19.67% at 450°C to 18.00% at 495°C and increased again to 19.67% at 550°C. Microstructural observations at 100× and 200× showed qualitative changes in the appearance, arrangement, distribution, and uniformity of the observed structure with increasing annealing temperature. Because grain size was not quantitatively measured, the microstructural interpretation was limited to visual comparison. The mechanical-property trend is consistent with a tendency toward material softening as annealing temperature increases. Among the tested conditions, 450°C provided the highest combination of tensile strength and hardness and was therefore considered the most optimal condition when these two parameters were prioritized.

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