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Investigating the effects of solution treatment parameters and artificial aging on hardness improvement of precipitation hardened 6061 Aluminum alloy

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Abstract

This study investigates the effects of solution treatment parameters-including temperature, holding time, and quenching media-on the hardness enhancement of wrought aluminum alloy 6061-T6 through precipitation hardening. The objectives of this research are to analyze the influence of solution treatment parameters on hardness enhancement, explore the correlation between the solutioning step and the artificial aging process, and optimize the heat treatment process to achieve improved hardness values. Specimens of 6061-T6 aluminum alloy initially exhibited a hardness of 102 HV. After heating to 500°C with holding times of 45, 60, and 75 minutes, followed by quenching in water and SAE 40 oil, Vickers hardness testing revealed significant changes: hardness dropped to 52 HV after solution treatment, then increased to 63 HV (21.15% increase) for 60 minutes and 64 HV (23.08% increase) for 75 minutes. After artificial aging at 210°C for 120, 180, and 240 minutes, the maximum hardness recorded was 113 HV, marking a 10.78% increase from the initial hardness. The quenching medium also influenced hardness; specimens quenched in SAE 40 oil showed improved hardness compared to those quenched in water, likely due to slower cooling rates that allow for better precipitate formation. The hardness enhancement is attributed to microstructural changes during heat treatment. Solution treatment promotes the dissolution of alloying elements, leading to the formation of fine precipitates during aging. These precipitates impede dislocation movement, thereby enhancing the alloy's strength through precipitation hardening. Thus, the density and distribution of these precipitates significantly contribute to the overall hardness enhancement observed in the 6061-T6 aluminum alloy.

Keywords:
6061-T6 aluminum alloy, solution treatment, hardness enhancement, precipitation hardening, quenching media, Vickers hardness, aging process, microstructural changes, precipitate formation

1 Introduction

Aluminum alloys play a crucial role in various industries, particularly in aerospace and automotive applications, due to their lightweight and high strength-to-weight ratio [1]. Among these alloys, wrought aluminum alloy 6061 is widely recognized for its excellent mechanical properties, good corrosion resistance, and favorable workability, making it a preferred choice in engineering applications [2]. Wrought aluminum alloy 6061 contains magnesium and silicon as its primary alloying elements, which enhance its mechanical properties and ease of fabrication. Its versatility allows for applications ranging from structural components to intricate parts in high-stress environments [3]. Hardness, a vital mechanical property, is essential for assessing the performance of materials under stress and wear conditions. The enhancement of hardness in aluminum alloys is significantly influenced by heat treatment processes, specifically solution treatment and aging. These processes promote the formation of fine precipitates within the alloy, contributing to increased hardness through mechanisms such as precipitation hardening [4][5].

Aluminum is a lightweight metal with a low density (2.7 g/cm³), high electrical and thermal conductivity, and excellent corrosion resistance, with a melting point of approximately 660°C (1220°F). The crystal structure of Aluminum is FCC, which provides good ductility for easy shaping. Aluminum can be strengthened through cold working and alloying. The main alloys of Aluminum include copper, magnesium, silicon, manganese, and zinc. In the industrial world, Aluminum alloys are widely used in the aviation, automotive, and food and beverage packaging industries [2].

Aluminum alloy 6061 has a composition of Al = 95.8-98.6%, magnesium (Mg = 0.8 – 1.2%), and silicon (Si = 0.4 – 0.8%). The phase diagram of Aluminum alloy 6061 illustrates the relationship between temperature and alloy composition, as well as the phases present within the alloy. Aluminum alloy 6061 can enhance its strength through the precipitation of intermetallic phases Mg and Si (Mg_2Si). The strength and hardness of Aluminum alloy Al 6061 can be increased through the dispersion of a new phase particle known as the second phase, Mg_2Si, as the β phase, with a very small and uniform size within the main phase, which is more dominant, Al, as the α phase, known as the matrix [6]. This dispersion process occurs through phase transformation resulting from appropriate heat treatment [7].

The automotive and aviation sectors utilize Aluminum alloys due to their ability to reduce weight and enhance efficiency [8]. Aluminum alloys are also extensively used in construction and electronics, with the added advantage of being recyclable without losing quality. Aluminum 6061 is a highly popular alloy in construction due to its combination of strength, durability, and ease of processing. Its primary applications include the manufacturing of structural components such as frames, columns, and beams, which leverage its lightweight properties to reduce loads [6]. This alloy is also used in window and door frames, as well as roofing systems, due to its corrosion and weather resistance. Furthermore, Aluminum 6061 is employed in construction equipment such as scaffolding and work platforms, as well as pipes and profiles for structural applications. In both interior and exterior design, this alloy is used for furniture and decorative elements, making it a top choice for various modern construction projects.

The mechanical properties of Aluminum alloys can be enhanced through the heat treatment process known as Precipitation Hardening, which is used to increase the strength and hardness of non-ferrous metal alloys such as Aluminum, copper, and magnesium. This process involves two stages: solution treatment and aging. In the first stage, the alloy is heated until all solute atoms dissolve into the solvent atoms and then rapidly cooled to create a supersaturated solid solution. Subsequently, in the second stage, the alloy is reheated to an intermediate temperature to form precipitate particles through diffusion, a process known as aging. During this process, the hardness and strength of the Aluminum alloy increase with aging time until they reach a maximum hardness, followed by a decline due to over-aging. Overall, the precipitation hardening heat treatment is highly beneficial for enhancing the mechanical properties of metal alloys, making them stronger and more resistant to deformation, which is crucial in many industrial applications, particularly in aerospace and automotive fields.

Previous studies have shown that aging temperature and time significantly affect the strength enhancement of Aluminum alloy 6061. At higher aging temperatures (190°C), the precipitation of strengthening elements occurs more effectively, contributing to increased material strength. However, if the temperature is too high, it can cause softening or degradation of the mechanical properties. Aging time also plays a role, with an optimal time of 2 hours allowing for effective formation of precipitate particles without causing softening. If the aging time is too short, not all strengthening elements may precipitate maximally, while if it is too long, excessive precipitation can actually reduce material strength. Therefore, the combination of appropriate aging temperature and time is crucial to achieving an optimal balance between strength and alloy toughness [9][10].

The aging process of Aluminum alloy 6061 at higher temperatures increases the nucleation rate of precipitate Mg_2Si, which contributes to enhanced hardness, strength, as well as percentage elongation and toughness. Results indicate that maximum mechanical properties, including tensile strength and toughness due to moderate grain size and uniform distribution of precipitate Mg_2Si [11]. Thus, selecting the appropriate aging and solid solution temperatures is critical for optimizing the performance of this alloy. The right combination of temperature and holding time is crucial for achieving the best alloy performance through efficient aging processes [12].

The optimal heat treatment parameters for strengthening Aluminum alloy 6061 include solution treatment followed by rapid cooling. The best artificial aging is performed, resulting in the ideal combination of strength and formability [13]. Heat treatment parameters significantly affect the mechanical properties of Aluminum 6061. Temperature and duration of heat treatment determine optimal precipitation formation, and it is also important to ensure proper dissolution of alloying elements. Therefore, precise control over all heat treatment parameters is crucial for achieving the best performance of the alloy [14][15].

Other Previous studies have extensively investigated the effects of aging time on the mechanical properties of Aluminum alloy. For instance, Sui et al. demonstrated that optimizing solution treatment parameters significantly enhanced the hardness of 6061 alloy [16]. The aging process and its role in precipitate formation, highlighting the correlation between aging time and hardness levels [17]. And conducted a comprehensive study on the effects of various quenching media on the hardness of 6061, revealing that water quenching yielded the highest hardness values compared to oil and air cooling [18]. Investigated the influence of aging temperature on the microstructural evolution of Aluminum alloys, demonstrating that higher aging temperatures led to coarser precipitates, which adversely affected hardness [19]. Despite these insights, gaps remain in understanding the specific parameters that yield the best results for hardness enhancement. Notably, few studies have systematically analyzed the interplay between solution treatment and aging, particularly in the context of wrought Aluminum alloys. This research aims to fill that gap by focusing on the optimization of heat treatment parameters for wrought Aluminum alloy 6061. The primary objectives of this research are: (1) to analyze the influence of solution treatment parameters on hardness enhancement, (2) to investigate the correlation between the solutioning step and the aging process, and (3) to optimize the heat treatment process for improved hardness values. By optimizing heat treatment, this research aims to enhance material properties, ensuring greater reliability and durability in critical applications.

2 Materials and experimental methods

The primary material used in this study is wrought Aluminum alloy 6061, sourced from a commercial supplier. This material was accompanied by a certificate of analysis confirming its composition and mechanical properties. To ensure the accuracy of the provided composition, a secondary analysis was conducted using Laser-Induced Breakdown Spectroscopy (LIBS), which allows for rapid and precise elemental analysis (The chemical composition of the Aluminum alloy is Al-97.88 wt%, Mg-0.88 wt%, Si-0.52 wt%, Fe-0.28 wt%, Cu-0.165 wt%, Cr-0.033 wt%, and Mn-0.043 wt%). The samples were prepared according to standard procedures to ensure consistent results, and the data obtained from LIBS were compared with the certified values to validate the material's composition. Specimens were prepared using manual milling to achieve the desired dimensions and surface finish. This milling process ensured uniformity and precision in the sample geometry, which is critical for the subsequent heat treatment and testing. The specimens underwent solution treatment in a Nauberman heating furnace at a temperature of 500°C, with holding times varied at 45, 60, and 75 minutes. Following solution treatment, the specimens were rapidly quenched in two different media: water and SAE 40 oil, a crucial step for retaining the desired microstructure. After 16 hours of storage, all specimens were aged at 210°C for varying durations of 120, 180, and 240 minutes. The schematic precipitation hardening heat treatment is shown in Fig. 1. Quenching was performed immediately after aging in either water or oil to finalize the heat treatment process. Hardness measurements were conducted using the Vickers hardness test. The process for preparing hardness test specimens by cutting the Aluminum alloy into shapes and sizes that conform to ASTM E 384-17 [20] Standard test method for micro indentation hardness of materials. The surface of the specimens was then polished to eliminate irregularities that could affect the test results. The specimens were subsequently cleaned of contaminants to ensure accuracy. The Vickers microhardness testing machine was prepared and calibrated.

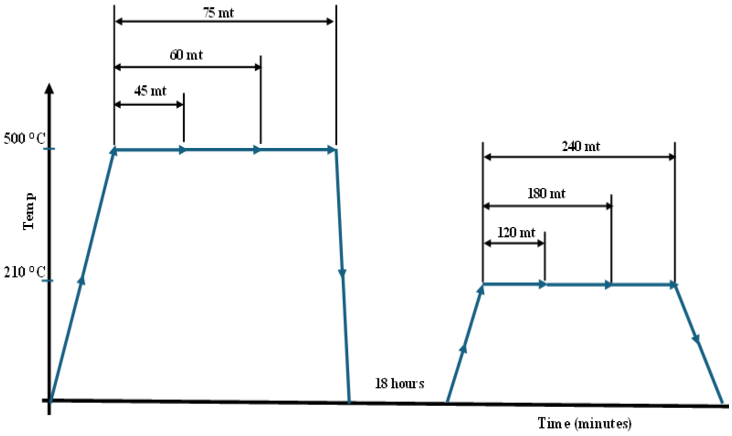


Fig. 1. Schematic of precipitation hardening heat treatment

3 Results and discussion

3.1 Analysis of hardness result

The results of the hardness tests conducted on the 6061 Aluminum alloy samples are summarized in Table 1. The data indicate variations in hardness values corresponding to different heat treatment parameters, specifically solution treatment temperatures, holding times, and quenching media. The maximum hardness achieved was 113 HV, observed in specimens treated at a holding time of 75 minutes and quenched in water. Comparative analysis of the hardness values reveals that longer holding times generally lead to increased hardness, with notable distinctions between the effects of water and SAE 40 oil as quenching media.

The hardness results illustrate a clear correlation between the heat treatment parameters and the mechanical properties of the alloy. Increased holding times enhance the homogenization of the microstructure, allowing for more effective precipitation during subsequent aging processes. Specifically, the results indicate that specimens subjected to longer holding times exhibit significantly higher hardness values, supporting the hypothesis that prolonged exposure at elevated temperatures facilitates improved diffusion of alloying elements.

Table 1. Result of the hardness test

Specimen	Precipitation hardening heat treatment						
	Stage 1 (Solutioning)				Stage 2 (Artificial aging)		
	Temp (°C)	Holding (minute)	Quench medium	Hardness (HV)	Aging temp	Aging time (minutes)	Hardness (HV)
Al 6061							102
Al 6061	500	45	Water	52	210°	120	61
Al 6061			Oil	52	210°		68
Al 6061			Water	52	210°	180	66
Al 6061			Oil	52	210°		78
Al 6061			Water	52	210°	240	77
Al 6061			Oil	52	210°		89
Al 6061	500	60	Water	59	210°	120	77
Al 6061			Oil	63	210°		79
Al 6061			Water	59	210°	180	101
Al 6061			Oil	63	210°		99
Al 6061			Water	59	210°	240	92
Al 6061			Oil	63	210°		100
Al 6061	500	75	Water	63	210°	120	98
Al 6061			Oil	64	210°		93
Al 6061			Water	63	210°	180	109
Al 6061			Oil	64	210°		107
Al 6061			Water	63	210°	240	113
Al 6061			Oil	64	210°		111

3.2 Effect of holding time and quenching medium at solutioning treatment (SHT) on the hardness.

Fig. 2 illustrates the influence of holding time and quenching medium on the hardness of wrought Aluminum alloy 6061 that was subjected to Solution Heat Treatment (SHT) at 500 °C.

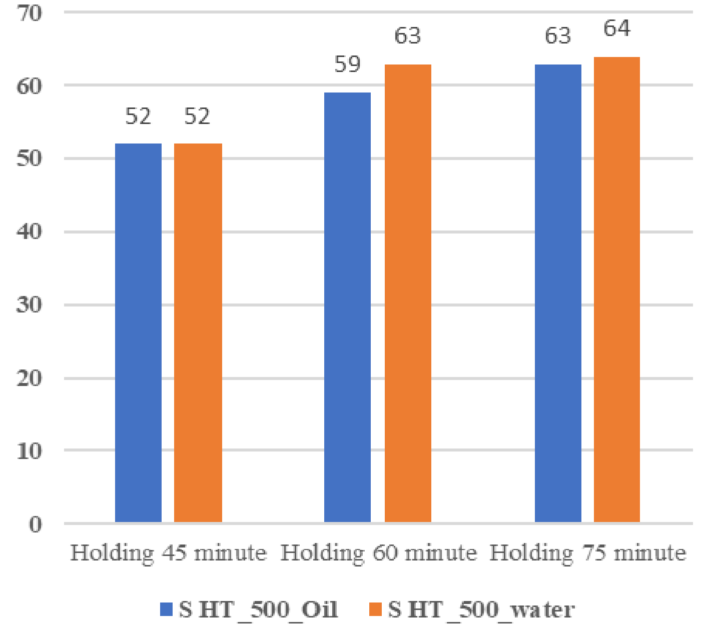


Fig. 2. Effect of holding time and quenching medium on the hardness of Al 6061 at SHT 500 °C

The effect of holding time during the SHT on hardness enhancement shows a significant trend. As the holding time increases from 45 minutes to 60 minutes and then to 75 minutes, the hardness values tend to rise. For a holding time of 45 minutes, the hardness values are 52 HV for oil and 59 HV for water, indicating that water quenching results in higher hardness due to its rapid cooling effect, which may promote finer microstructural features. At a holding time of 60 minutes, the hardness values increase to 63 HV for both quenching methods, suggesting that the extended holding time allows for better homogenization of solid solution and solute retention, leading to enhanced precipitation during subsequent aging. Finally, at 75 minutes of holding time, the hardness values slightly rise to 64 HV for water quenching, while remaining at 63 HV for oil quenching. This minimal increase implies that the benefits of longer holding times plateau at this duration, particularly for water quenching. Overall, the data emphasize that both holding time and quenching medium significantly affect the hardness of wrought Al 6061, with water quenching generally yielding better results.

3.3 Correlation Between Solutioning and artificial aging in enhancing hardness

The analysis of the correlation between solution treatment and artificial aging at 210 °C in enhancing the hardness of Aluminum alloy AA 210 reveals significant insights, as shown in Fig. 3.

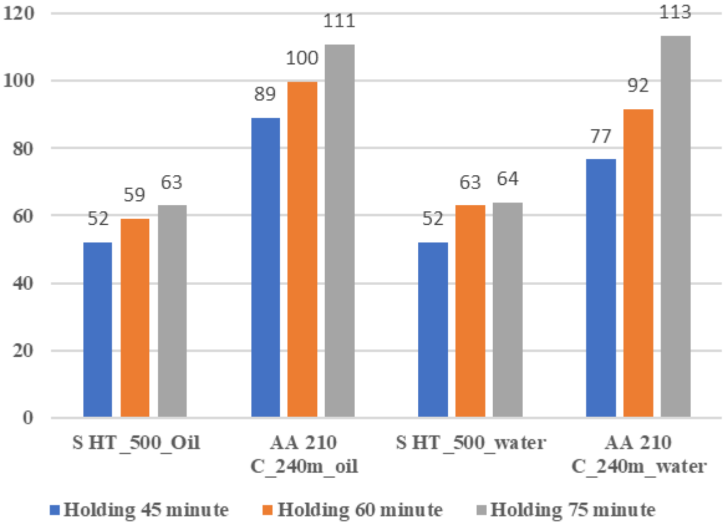


Fig. 3. Impact of solution treatment and artificial aging at 210 °C on the hardness of wrought Aluminum alloy 6061

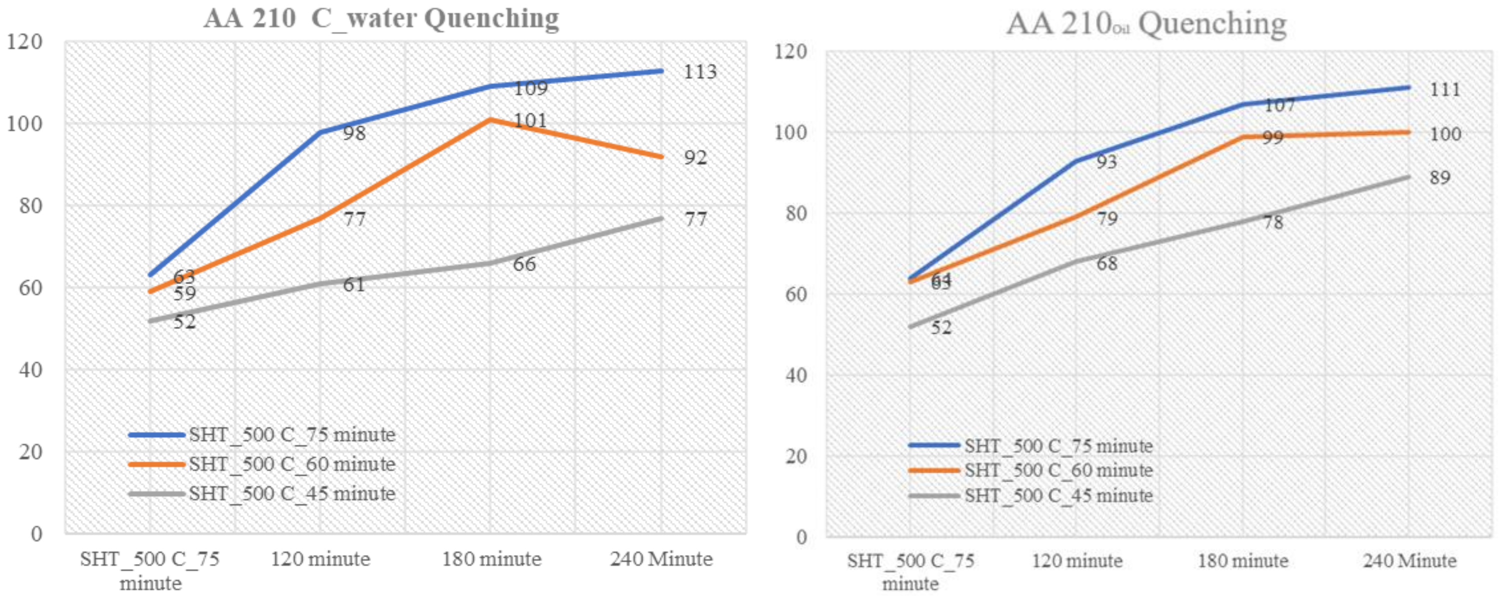
The data indicate that increasing the holding time during solution treatment positively impacts hardness values across both quenching mediums, oil and water. The water-quenching method consistently yields superior hardness values, achieving 113 HV at 75 minutes of holding time, compared to 111 HV for oil quenching. This suggests that the rapid cooling associated with water quenching promotes finer microstructural features and more effective precipitation during aging. Overall, the findings highlight a strong positive correlation between solution treatment and artificial aging at 210 °C in enhancing the hardness of Al 6061.

Based on the analysis of the correlation between solution treatment and artificial aging in enhancing the hardness of wrought Aluminum alloy 6061, the optimal parameters for achieving maximum strengthening can be concluded as follows. For SHT, a holding time of 60 minutes is recommended, as this duration effectively balances solute retention and homogenization, resulting in a hardness value of 63. However, extending the holding time to 75 minutes can further enhance hardness, particularly when coupled with water quenching, which achieves a hardness of 113. For artificial aging, conducting the process at 210 °C is optimal. Therefore, the integration of these parameters, holding 75 minutes for SHT and 210 °C for artificial aging, will facilitate the achievement of superior mechanical performance in Aluminum alloys so far.

Homogenization of the solution during the SHT stage is closely linked to the formation of precipitates during the artificial aging stage, both of which are critical for determining the hardness of Aluminum alloys. During SHT, the alloy is heated to elevated temperatures to dissolve alloying elements such as magnesium and silicon into the Aluminum matrix, achieving optimal solid solution homogeneity. This process reduces segregation of alloying elements and ensures a uniform distribution throughout the matrix. Following SHT, the alloy is rapidly cooled (quenched) to lock the alloying elements in solution, and upon aging, these elements begin to precipitate. Effective homogenization allows alloying elements to be present in optimal concentrations, resulting in finer and more uniformly distributed precipitates. These precipitates impede dislocation movement within the matrix, thereby enhancing hardness and strength. Furthermore, well-distributed precipitates can interact with one another to form a stronger network, increasing mechanical stability. Thus, the homogenization of the solution during the SHT stage is a critical step that determines the quality of precipitate formation during artificial aging, maximizing strengthening potential and significantly contributing to the enhancement of the hardness of Aluminum alloys.

3.4 The impact of artificial aging times on enhancing the hardness of 6061 Aluminum alloy

The influence of SHT parameters and artificial aging on the hardness improvement of wrought Aluminum alloy 6061 is shown in Fig. 4. Fig. 4 presents the effects of SHT durations on the hardness of wrought Aluminum alloy 6061. The first graph depicts the hardness values achieved with oil quenching, showing a clear trend of increasing hardness as the holding time in the SHT process is extended. The second graph illustrates the results for water quenching, which consistently yields higher hardness values compared to oil quenching at all durations. Both figures highlight the significance of optimizing SHT parameters and quenching methods to enhance the mechanical properties, providing valuable insights into the treatment processes for this Aluminum alloy.



(a) (b)

Fig. 4. Influence of SHT parameters and artificial aging on hardness improvement of wrought Aluminum alloy 6061

Both figures reveal the significant impact of aging time on the hardness of Aluminum alloy 6061. In the oil quenching scenario, hardness values increase notably with aging time, from 52 HV to 111 HV for a 75-minute holding time of SHT 500 °C and 240 minutes of aging time, demonstrating effective precipitation of strengthening phases. In contrast, the water quenching graph shows lower initial hardness values, with the 75 minutes at 59 HV and reaching 113 HV after 240 minutes. This suggests that while water quenching cools the alloy more rapidly, it may lead to less effective microstructural evolution. The findings indicate that longer aging times enhance hardness due to improved precipitate formation. If the aging time were increased further, hardness would likely continue to rise, provided that precipitate coarsening does not occur, thereby maximizing the mechanical properties of the alloy. This emphasizes the critical role of aging duration in optimizing the performance of Aluminum alloys.

Overall, while both quenching methods result in increased hardness with aging time, the water quenching process appears to yield lower hardness values compared to oil quenching, likely due to the rapid cooling dynamics that influence the precipitate formation and microstructural stability. The differences in the cooling rates and their effects on the alloy's properties highlight the importance of quenching medium selection in maximizing the mechanical performance of Aluminum alloys. Optimizing the parameters of both SHT and aging is essential for achieving the desired hardness of wrought Aluminum 6061.

4 Conclusions

This experimental investigation confirms that heat treatment parameters strongly govern the hardness evolution of 6061 aluminum alloy. Both the solution treatment stage and subsequent artificial aging are interdependent, and their optimization is critical for achieving maximum strengthening.

The three key highlights are: Firstly, the parameters of solution treatment, including temperature, holding time, and quenching medium, significantly affect the hardness improvement of wrought aluminum alloy 6061 through precipitation strengthening. Secondly, increasing the holding time from 45 to 75 minutes enhances hardness values due to improved diffusion of alloying elements and microstructural homogenization. The maximum hardness reached was 113 HV for specimens held for 75 minutes and quenched in water. Thirdly, a clear correlation exists between the solutioning phase and the strengthening effects of artificial aging. Longer-held specimens showed greater hardness increases after aging, indicating that a more homogeneous microstructure promotes effective precipitate formation. And fourthly, the quenching medium also impacts hardness, with specimens quenched in SAE 40 oil achieving equal or higher hardness than those quenched in water. This variation is likely due to different cooling rates affecting precipitate size and distribution.

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