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Effect of quenching medium, solution treatment, and aging parameters on mechanical properties of Aluminum alloy 6061

Pshtiwan M. Karim[a], **Rekawt R. Amin**[a], **Hawre F. Amin**[a*], **Abbas I. Khwakaram**[a], **Omer S. Mahmood**[b]

[a] Sulaimani Technical Institute, Sulaimani Polytechnic University, Sulaumaniyah, Iraq.
[b] Mechanical and Manufacturing Engineering Dept., Sulaimani Polytechnic University, Sulaumaniyah, Iraq.
*Corresponding author Email: hawre.amin@spu.edu.iq

HIGHLIGHTS

- How quenching medium and aging parameters affect the mechanical properties of Aluminum alloy 6061.
- Sesame oil was the optimal quenching medium among sesame, sunflower, and corn oils.
- Ultimate tensile strength was improved significantly, exceeding twice the value of the annealed sample.

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ABSTRACT

This study demonstrates the effect of quenching medium, solution treatment, and aging parameters on the mechanical properties of Aluminum alloy 6061. To select an optimal quenching medium from three distinct quenching media (corn, sunflower, and sesame oil), solution heat treatment was conducted on three impact test samples at 545 ℃ for 2 hours, and then quenching was conducted in the mentioned quenching medium. Consequently, sesame oil demonstrated the lowest shock absorption rate; thus, sesame oil was selected as the quenching medium. As a result, every sample for tensile, hardness, and impact tests underwent solution heat treatment at 545 ℃ for 2 hours, followed by quenching in sesame oil to room temperature, and subsequent artificial aging at temperatures of 180 ℃, 195 ℃, and 210 ℃ for 1, 2, 4 hours. Considerable enhancements in the mechanical properties were observed in tensile strength value and hardness while the ductility decreased. It was observed that the best result was achieved by aging at 195 ℃ for 4 hours, increasing the ultimate tensile strength to 351.413 N/mm^2 from the initial value of 260 N/mm^2 for the as-received specimen; this is attributed to the formation of finely dispersed grains. In contrast, the ultimate tensile strength for the annealing condition decreased to 152.020 N/mm^2 due to forming a coarser grain size. Furthermore, the highest hardness value achieved is 39.10 HRB, achieved by aging at 195 ℃ for 4 hours, compared to the hardness value achieved by annealing conditions at 18.23 HRB.

1. Introduction

Aluminum alloys are among the most important engineering materials, attracting considerable attention from researchers due to their exceptional properties, including lightweight, excellent thermal and electrical conductivity, high corrosion resistance, and ease of fabrication [1-3]. Aluminum alloys have broad applications in the construction, automotive application, and aerospace industries, especially due to the weight ratio to the strength being premium compared to other engineering materials. As it has low density, Aluminum alloys are considered a lightweight material [4-6]. Better fuel economy and less environmental impact in both the automotive and aerospace industries are always the case considerations of the companies working in these fields. Therefore, designers and researchers are trying to improve the mechanical properties of Aluminum alloys [7,8].

Two common techniques can enhance the mechanical properties of aluminum alloys: one way is by adding specific alloys to aluminum, and the other technique is by conducting heat treatment of the alloy. Metal Matrix Composites is a technique recently used by many researchers in which nanoparticles such as nano alumina particles Al_2O_3, nano silicon carbide SiC, and nano titanium dioxide particles TiO_2 are used as reinforcements in Aluminum matrix to improve mechanical properties of Aluminum alloy such as toughness, wear resistance, thermal conductivity, and hardness [9,10].

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

Heat treatment of Aluminum alloys is a widespread method to enhance the mechanical characteristics of Aluminum alloy series that can be heat treated. Solution treatment and aging, especially artificial aging, are commonly utilized [11-13]. Aluminum alloy 6061, is classified as a 6XXX series alloy that can be heat treated to improve its mechanical properties [14,15].

Precipitation hardening, in which the solute atoms are dissolved in the aluminum lattice at elevated temperatures, followed by quenching and aging to preserve the resulting solid solution. While this process is ongoing, the solute atoms "Mg and Si," which are the major solutes, diffuse through the matrix and form precipitates, consequently enhancing the mechanical characteristics of the Aluminum alloy [16-18]. Heat treatment parameters are closely related to aluminum alloys' mechanical properties. Although much research has been done on this alloy by researchers applying different parameters, specific temperatures, and time ranges, this may improve its mechanical properties further.

In this study, the mechanical properties of Aluminum alloy 6061 subjected to solution heat treatment and artificial aging were investigated and discussed; the focus was mainly on the aging parameters, especially aging time; three close aging times were selected to investigate the effect of each specified time on the mechanical properties of Aluminum alloy 6061. Significant mechanical properties were investigated, such as ultimate tensile strength and hardness values. The research found that a minor difference in aging temperature at 15 minutes led to a substantial difference in mechanical properties. Meanwhile, each proposed different aging time, such as the ultimate tensile strength and hardness values, achieved a crucial enhancement in mechanical characteristics.

2. Experimental method

2.1 Material

Aluminum alloy 6061 was used for this study, and its chemical composition is shown in Table 1.

Table 1: Aluminum alloy 6061 Chemical composition was used in this experiment

Element	Si	Cu	Fe	Mn	Cr	Mg	Zn	Other	Al
Composition %	0.49	0.22	0.15	0.02	0.07	0.88	0.04		REM

2.2 Preparation of samples for testing

Two sets of specimens were prepared to conduct this experiment:

1) A 10 mm-thick Aluminum alloy 6061 plate was used to prepare Charpy V-notch specimens shown in Figure 1 (c) at Sulaimani Technical Institute Figure 1 (a and b) Shows the preparation steps of the Charpy V-notch specimens. 15 Specimens were made according to the ASTM E23 standard, as shown in Figures 1 and 2.

(a) **(b)** **(c)**

Figure 1: (a,b,and c) Preparation steps of Charpy V-notch specimens from a 10 mm-thick Aluminum alloy 6061 plate

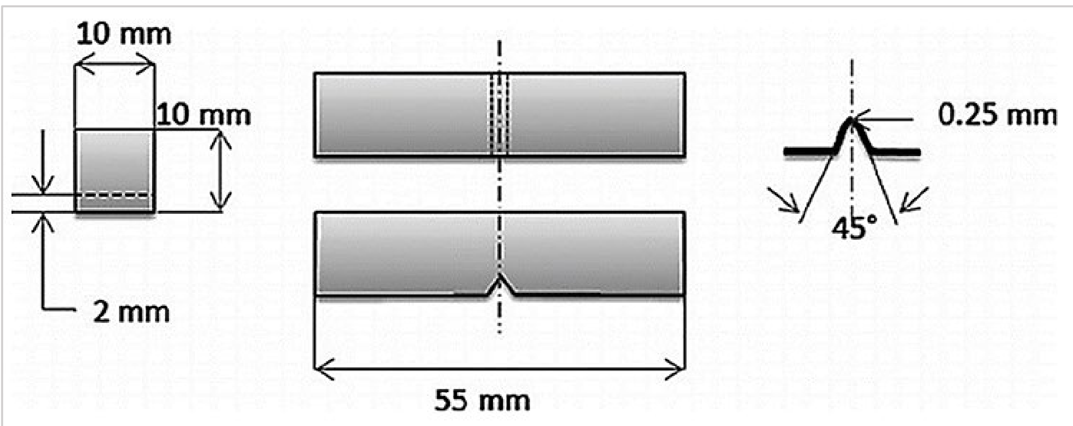

Figure 2: The dimensions of the Charpy V-notch specimen complies with ASTM E23 standard.

2) An Aluminum alloy 6061 round bar (20 mm) diameter was used to prepare tensile test specimens. A CNC turning machine at Sulaimani Technical Institute made 15 Specimens according to the ASTM E8 standard. Figure 3 shows the Tensile Test Specimen preparations. Figure 4 shows the specimen dimensions according to the ASTM E8 standard.

Figure 3: Tensile test specimens are manufactured in Sulaimani Technical Institute using a CNC turning machine

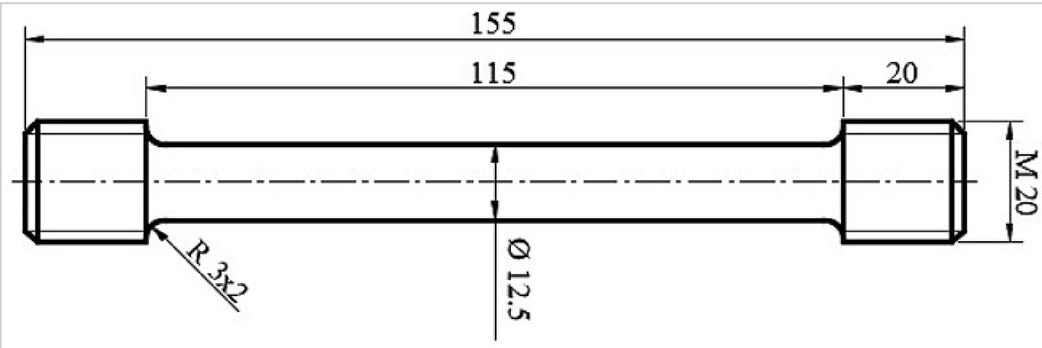

Figure 4: The dimensions of the tensile test specimen complies with ASTM E8 standard

To ensure the tensile strength value of the as-received Aluminum alloy 6061 material for later comparison, a tensile test was conducted on the specimen in its original condition before it underwent any heat treatment process. A 1000KN Universal Testing Machine was used at Suly Steel Company (For steel rebar production) to perform the test.The Ultimate tensile strength value for the as-received specimen of Aluminum alloy 6061 was 260 N/mm^2.

2.3 Heat treatment

To select the optimal quenching media, three impact test samples were heated at 545 °C for 2 hours in a high-temperature Muffle Electric Furnace at Sulaimani Polytechnic University/Technical College of Engineering at the heat treatment laboratory.

The suitable temperature 545 °C is selected for a solution treatment of Aluminum alloy based on previous studies [5,15]. Eventually, Charpy V-notch specimens were quenched in three different media (sesame oil, sunflower oil, and corn oil). A Charpy impact test was performed on the specimens. As a result, the sample quenched in sesame oil showed the lowest impact energy value of 26.54 Joule. Table 2 displays the impact test results for the specimens in three different quenching media (sesame, sunflower, and corn oil).

Table 2: Charpy V-notch impact test result for different quenching medium, solution heat treated at 545 °C for 2 hours

Al alloy 6061 Sample No.	Quenching Medium (Oil)	Charpy Impact values Av (Joule)	Optimum Medium
1	Sesame 545 °C	26.54	Sesame oil
2	Corn 545 °C	37.16	
3	Sunflower 545 °C	42.18	

It is obvious that the optimal quenching medium for this experiment study is sesame oil; accordingly, the specimens for both the tensile and impact tests were heated in the furnace at 545 °C for 2 hours and subsequently cooled to room temperature by quenching in sesame oil, then artificially aged at three different temperatures at 180 °C, 195 °C and 210 °C for three different periods of times 1,2,4 hours. In this process, the samples were aged at different temperatures for various periods to identify each parameter's effect on the mechanical properties of aluminum alloy 6061. Meanwhile, two samples from the tensile and impact tests were annealed for later comparison. The samples were heated to 545 °C in a furnace and maintained in the furnace for 24 hours to restore the samples to their normal state.

3. Results and discussion

Table 3 displays the tests conducted on all samples for this study for easy comparison. However, the tensile, hardness, and impact test results will be discussed separately.

Table 3: Overall results of hardness, tensile, and impact tests

Sample No.	Aging temperatures	Aging hours	Charpy Impact values Av (Joule)	Hardness HRB	Tensile Strength (N/mm^2)
1		1	33.50	21.65	276.423
2	180 °C	2	29.65	22.42	291.152
3		4	27.89	26.43	334.345
4		1	29.16	23.60	304.887
5	195 °C	2	22.50	32.90	340.715
6		4	19.11	39.10	351.413
7		1	36.25	20.25	295.531
8	210 °C	2	26.40	27.05	334.246
9		4	28.78	24.45	328.722
10	Annealing 545 °C / 24 hrs.		40.25	18.23	152.020

3.1 Tensile test

As stated in the earlier section of this study, a 1000 KN Tensile Testing Machine at Suly Steel Co., in Iraq was used to perform Tensile tests on the specimens already heat-treated and artificially aged. Stress and strain curves are shown in Figures 5 to 7.

Figure 5 shows the Stress and Strain curve of the samples quenched at 180 °C at three different times. The ultimate tensile strength reaches its peak at 180 °C for 4 hours with a value of 334.345 N/mm^2, which is more than double the ultimate tensile strength of the annealed sample (152.020 N/mm^2), showing a significant enhancement in the mechanical property of the alloy. In contrast, the results of the other two aging times within the same temperature, 180 °C, 1 and 2 hours aging time resulted in lower improvement of the ultimate tensile strength 276.423 N/mm^2 and 291.152 N/mm^2 respectively; this shows that more aging time was needed to form a finely dispersed grain.

Figure 6 illustrates the maximum ultimate tensile strength of (351.413 N/mm^2) obtained at 195 °C for 4 hours in this study, and the second highest value of the ultimate tensile strength (340.715N/mm^2) is also at 195 °C for 2 hours. Therefore, 195 °C can be considered the optimum aging temperature for Aluminum alloy 6061.

Figure 7 shows the highest ultimate tensile strength achieved (334.246 N/mm^2) at 210 °C for 2 hours. Here, the tensile strength value is almost the same as the highest value of 180 °C 4 hours which is (334.345 N/mm^2). It can be concluded that for improvements in the mechanical properties tensile strength, both time and temperature are necessary and affect the properties of the alloy. Here, when the temperature is low 180 °C more time 4 hours was needed to achieve nearly the same result of tensile strength with just 2 hours when heated to a higher temperature 210 °C.

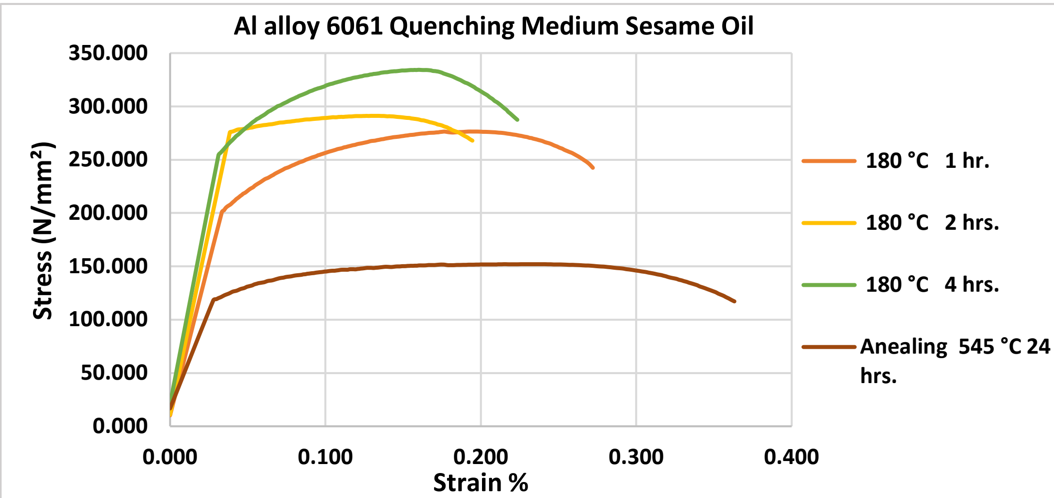

Figure 5: Stress vs. Strain curves for Aluminum alloy 6061, solution heat treated in sesame oil and artificially aged at 180 °C for (1,2,4) hrs. The sample was annealed at 545 °C for 24 hrs

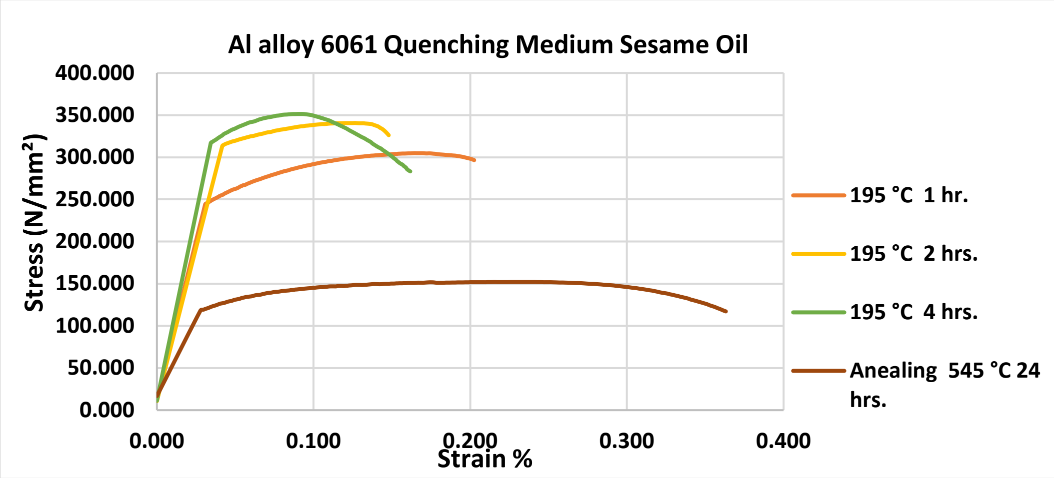

Figure 6: Stress vs. Strain curves for Aluminum alloy 6061, solution heat treated in sesame oil and artificially aged at 180 °C for (1,2,4) hrs. The sample was annealed at 545 °C for 24 hrs

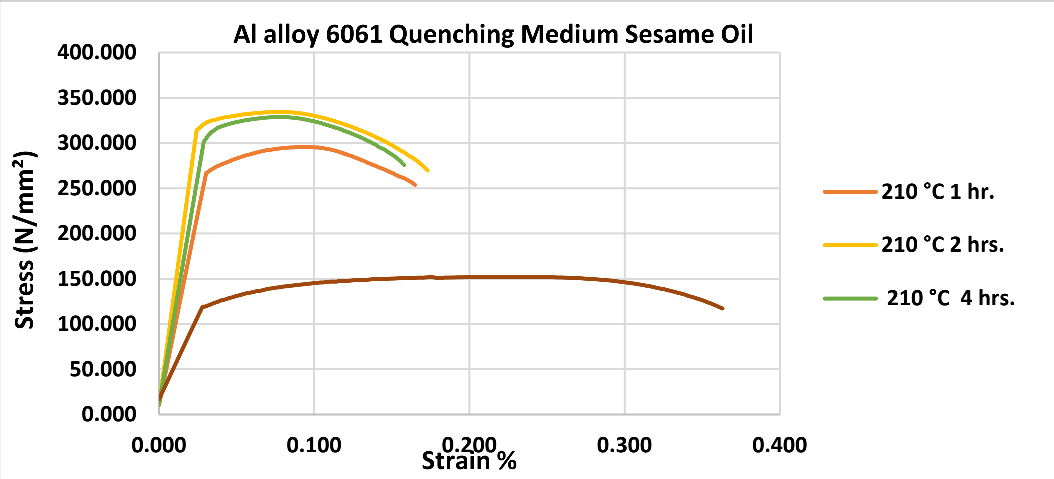

Figure 7: Stress vs. Strain curves for Aluminum alloy 6061, solution heat treated in sesame oil and artificially aged at 180 °C for (1,2,4) hrs. The sample was annealed at 545 °C for 24 hrs.

3.2 Hardness test

Hardness tests were conducted on the Charpy V-notch samples after the solution treatment and artificial aging on a Brinel Testing Machine at Mass Iron and Steel Industry Co., Iraq. For greater accuracy, the values in Figure 8 represent the average of three hardness test measurements taken at different locations on each sample. Figure 9 demonstrates the hardness values as a function of the artificial aging time for the samples. The sample artificially aged at 195 °C for 4 hours achieved the highest hardness value (HRB 39.10), which is completely logical. The same aging temperature, 195 °C for four hours, recorded the highest ultimate tensile strength.

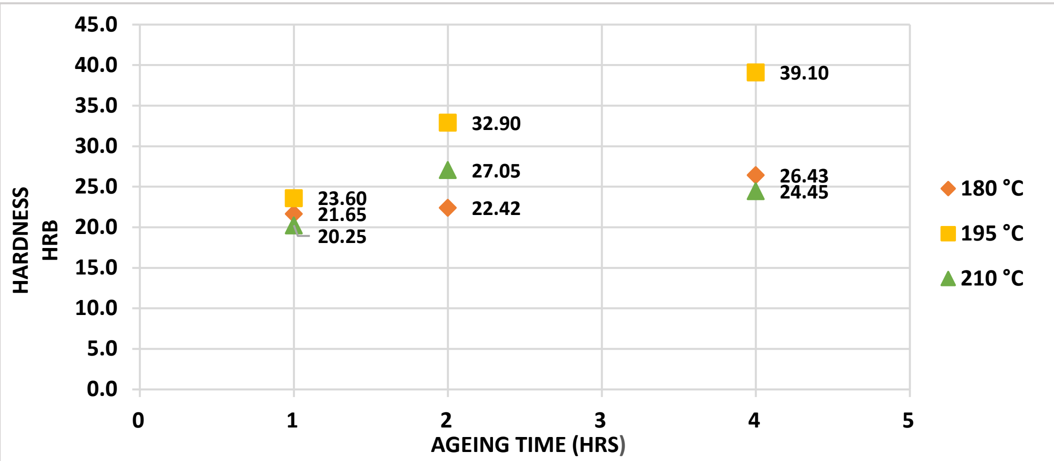

Figure 8: Hardness values for various aging times and temperatures for Aluminum alloy 6061

3.3 Impact test

At Sulaimani Polytechnic University/Mechanical and Manufacturing Engineering Department-Iraq, Charpy impact tests were conducted on the Charpy V-notch samples on the Charpy impact testing machine. Figure 9 illustrates the results of the Charpy impact test conducted on Aluminum alloy 6061 samples, which were quenched in sesame oil and artificially aged at 180 °C,195 °C, and 210 °C for 1, 2, and 4 hours. It is obvious that the sample solution treated in sesame oil and aged at 195 °C for 4 hours, has the lowest absorbed impact energy (19.11 Joule); this is completely logical, while the same aging temperature at 195 °C for four hours, recorded the Maximum hardness value (HRB 39.10). In contrast, the annealed condition has impact energy (40.25 Joule). This is due to the slow cooling rate of the sample, which leads to the formation of coarse grain size and, as a result, makes the alloy more ductile.

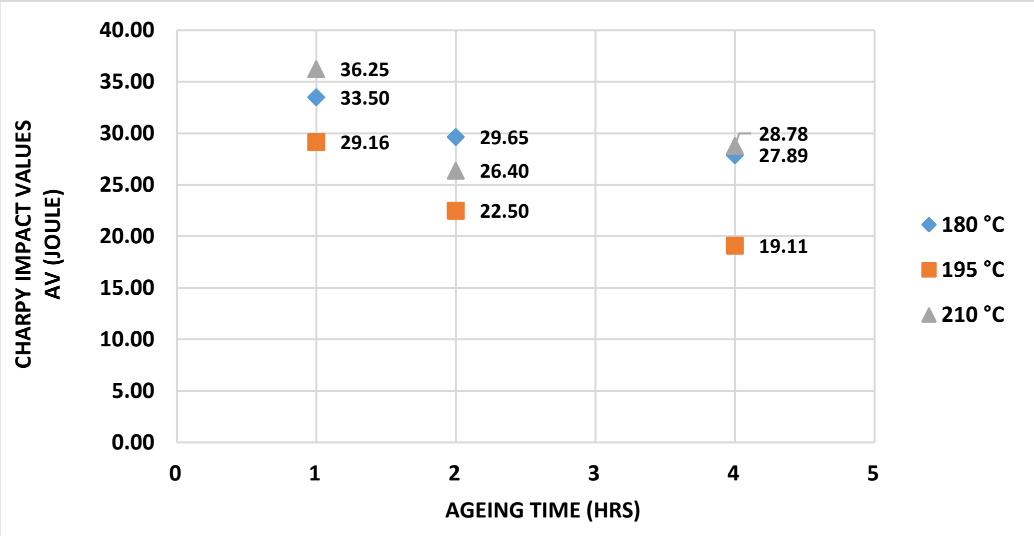

Figure 9: Charpy impact test values versus various aging time and temperature for Aluminum alloy 6061

4. Conclusion

This study investigated how precipitation hardening affects the mechanical characteristics of Aluminum alloy 6061. The influence of solution treatment and aging parameters on the mechanical characteristics of Aluminum alloy 6061 was studied. The study can be concluded as follows:

1) The quenching medium significantly affects the heat treatment process, and selecting the proper quenching medium is crucial.
2) The best result was achieved from the highest aging time (4 hours) at 195 °C, with an ultimate tensile strength of 351.413 N/mm^2, hardness of 39.10 HRB, and impact value of 19.11 Joule.
3) All results of aging time 1 hour for all the aging temperatures 180 °C, 195 °C, and 210 °C compared to the annealed condition of the material have no substantial enhancements in the mechanical characteristics of the alloy. A possible explanation is that 1 hour of aging time may not be enough for precipitation hardening to replace the alloy.
4) Cooling rate affects the strength of heat-treated samples. A faster cooling rate, as in the case of sesame oil, resulted in higher strength than a slow cooling rate under the annealing condition.

Author contributions

Conceptualization, **P. Karim; R. Amin; A. Khwakaram; O. Mahmood;** and **H. Amin**; data curation, **H. Amin**.; formal analysis, **H. Amin**.and **O. Mahmood**.; investigation, **R. Amin** .and **A. Khwakaram**; methodology, **H. Amin**. and **O. Mahmood**; project administration, **A. Khwakaram**, resources, **R. Amin**.; software, **H. Amin**.; supervision, **P. Karim**. and **H. Amin**.; validation, **H. Amin**.., **P. Karim.** and **O. Mahmood**.; visualization, **H. Amin**. and **P. Karim**.; writing—original draft preparation, **H. Amin**.; writing review and editing, **H. Amin**. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data supporting this study's findings are available on request from the corresponding author

Conflicts of interest

The authors declare that there is no conflict of interest.

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