Vokasi Unesa Bulletin of Engineering, Technology and Applied Science (VUBETA)
https://journal.unesa.ac.id/index.php/vubeta
Vol. 2, No. 1, 2025, pp. 48~56 DOI: 10.26740/vubeta.v2i1.34984
ISSN: 3064-0768

Microstructure and Hardness Study of Al6061 Resulting from Artificial Aging

Dewi Izzatus Tsamroh[1*], Dewi Puspitasari[2], Poppy Puspitasari[3], Mazli Mustapha[4]
[1]Diploma IV of Manufacturing Engineering Technology, Faculty of Vocational Studies, Universitas Negeri Malang, Malang, Indonesia
[2]Department of Mechanical Engineering, Faculty of Vocational, Universitas Negeri Surabaya, Surabaya, Indonesia
[3]Mechanical and Industrial Engineering Department, Faculty of Engineering, Universitas Negeri Malang, Malang, Indonesia
[4]Mechanical Engineering Department, Universiti Teknologi PETRONAS,Persiaran UTP, 32610 Seri Iskandar, Perak, Malaysia

Article Info

Article history:

Received September 24, 2024
Revised December 13, 2024
Accepted February 6, 2025

Keywords:

Microstructure
Image-J
Hardness
Al6061
Artificial Aging

ABSTRACT

This research aimed to improve the mechanical properties of Al6061 alloy through artificial aging heat treatment. This research employed a laboratory-based experimental method. The Al6061 alloy was heated in a muffle furnace at a temperature of 480°C and held for 30 minutes. Next, rapid cooling (quenching) was carried out using cooling media of dromus oil. Then, the specimens were reheated at 190°C for 2, 4, and 6 hours for the artificial aging process. The heat-treated specimens were tested for microstructure and hardness numbers. The obtained data were compared and analyzed using ImageJ software. The research results showed that the smallest grain diameter, 47.633 µm, was observed in specimens subjected to artificial aging for 4 hours. In this specimen, the β-Mg2Si phase was found to be 19.752 %. The highest hardness number was obtained in specimens with the same variation, which was 110.8 HR_E.

1. INTRODUCTION

Aluminum is a non-ferrous alloy that is widely used in several industrial fields, including the machining industry, automotive industry, and aircraft industry [1]–[4]. Aluminum alloys possess several advantageous properties. In general, they are lightweight, easy to form, relatively inexpensive, and corrosion-resistant [5]–[7]. However, aluminum alloys have lower mechanical properties compared to other commercial metals such as iron and steel.

Aluminum alloys consist of several series, these qualifications are divided based on the elements that make up the aluminum alloy [8][9]. One type of aluminum alloy that is widely used and researched is the Al6061 alloy [10]–[12]. Al6061 is a widely used aluminum alloy in various engineering and industrial applications [13]–[15]. This alloy belongs to the 6000 series, known as aluminum-magnesium-silicon alloys [16][17]. This alloy is commonly used in the aerospace industry, automotive industry, construction, and marine industry [3][18]. Al6061 alloy is used in several fields due to its excellent weldability and ability to undergo heat treatment. Al6061 alloy is widely used in applications requiring a balance of strength, corrosion resistance, and machinability due to the following reasons: Al6061 has a good strength-to-weight ratio, making it suitable for structural applications [19]. It can also be heat-treated (T6 temper) to achieve higher mechanical strength, allowing it to withstand substantial loads while remaining lightweight [20]–[22]. It is highly resistant to corrosion, particularly in atmospheric and marine environments, due to its natural oxide layer and the presence of magnesium and silicon in the alloy composition. Al6061 is easily machinable, allowing for efficient processing, cutting, and shaping [23]. This makes it ideal for applications requiring precision engineering or complex geometries. Al6061 exhibits excellent weldability, especially when proper techniques are used, making it suitable for fabricating welded structures. Compared to other high-strength alloys, Al6061 offers an attractive balance between performance and cost, making it a practical choice for a wide range of industries.

*Corresponding Author
Email: dewi.tsamroh.fv@um.ac.id

These properties make Al6061 alloy particularly popular in industries such as aerospace, automotive, marine, construction, and consumer electronics, where reliability and performance are critical.

Several types of heat treatment that can be applied to improve the mechanical properties of the Al6061 alloy are T6 (solution heat treated and artificially aged), T5 (cooled from an elevated temperature shaping process and artificially aged), and T4 (solution heat treated and naturally aged) heat treatment [24]–[26]. The following shows the chemical composition of Al6061. It can be seen in Table 1.

Table 1. Chemical composition of Al6061

Element	% weight
Mg	1.08
Fe	0.17
Si	0.63
Cu	0.32
Mn	0.52
V	0.01
Ti	0.01
Al	Balance.

Artificial aging is a heat treatment process that enhances the strength of aluminum [27][28]. Usually artificial aging is done after the solution heat treatment process, this aims to form deposits or precipitates. Precipitation hardening is a heat treatment process on aluminum or steel alloys, which aims to increase the strength and hardness of the material in aluminum [29]. The increase in strength occurs due to the uniform distribution of nanoparticles formed during heat treatment, which inhibits dislocation movement [5]. These small particles are often referred to as precipitates in aluminum alloys. Dislocation of small particles in heat-treated specimens can be analyzed by microstructure testing [30].

There are several previous studies related to heat treatment of aluminum alloys, previously researchers conducted multistage artificial aging on duralium. Researchers compared the results of single step and triple step artificial aging on the tensile strength of duralium alloys with artificial aging temperatures at an artificial aging temperature of 150°C [31]. The results showed that duralium alloys with triple step artificial aging had higher tensile strength. Other research related to the optimization of artificial aging parameters using the Taguchi method, shows that the artificial aging parameters to obtain optimum results are obtained at artificial aging temperature parameters of 200°C, holding time of 4 hours, and two artificial aging steps [32]. Previous research related to artificial aging heat treatment on Al6061 alloy at a temperature of 200°C with varying holding times showed that the highest hardness was obtained in specimens with a holding time of 4 hours [33]. Other research related to artificial aging of Al6061 alloy with temperature variations shows that the best results are found in specimens with a temperature of 190°C [34]. Meanwhile, specimens treated with artificial aging at temperatures of 200°C and 225°C experienced overaging [11]. Based on the description above, this study aims to improve the mechanical properties of Al6061 alloy through natural aging (T4) and artificial aging (T6) treatments. The structure of this paper consists of Section 2 on the method, Section 3 contains the results and discussion, and Section 4 contains the conclusion.

2. METHOD

2.1. Materials

The material used in this study is Al6061, a 6xxx series aluminum alloy. Al6061 alloy is one of the popular aluminum alloys, mainly used in applications that require a combination of strength, corrosion resistance, and good machinability [35]–[38]. Table 2 presents the tools and materials used in this study along with their specifications.

Table 2. Materials and tools

Name	Specification
Furnace	Muffle furnace, 220V, 50Hz, 12A, 2,7Kw, 1100°C
Microscope optic	Nikon Eclipse LV100ND, magnification 200x
Rockwell hardness tester	AFFRI 206.Rt-206.RTS, major load 100kg, 1/8” steel ball indenter
Materials	Aluminium Alloy Series 6061
Dromus oil	Universal soluble cutting oil
Sand paper	Grit 500, 600, 1000, 1200
Etching liquid	HF

2.2 Methods

This experimental research, using descriptive analysis, aims to determine the effect of artificial aging holding time on the microstructure and hardness of Al6061 alloy. The research scheme is shown in Figure 1 and Figure 2. Figure 1 shows the research steps, while Figure 2 shows the heat treatment diagram carried out by the researcher. This research begins with a literature study, namely comparing the results of previous studies and other studies that are relevant to the discussion to determine the variables/parameters in this study.

Furthermore, the preparation of tools and materials is carried out, namely the formation of specimens based on the ASTM E18 standard for hardness testing with dimensions of 30mm x 25mm x 15mm. Next, the artificial aging heat treatment process is carried out with variations in holding time. Microstructure and hardness testing is carried out on artificial aging specimens. The collected data is analyzed using the help of Image-J software. Analysis using Image-J software will produce data in the form of phase percentage and grain size [39]–[41].

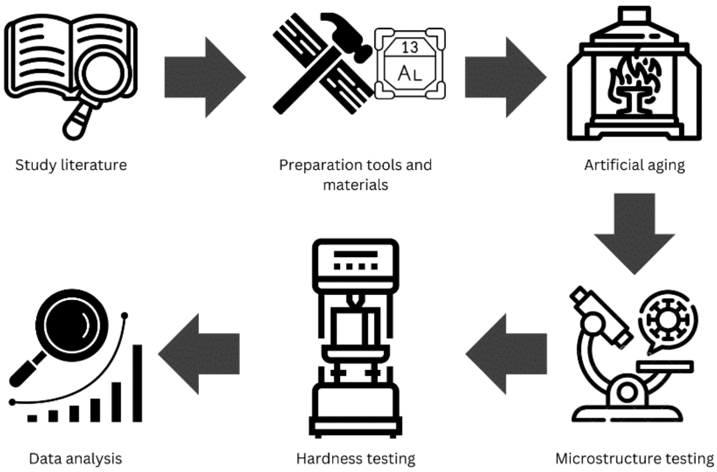


Figure 1. Research procedure

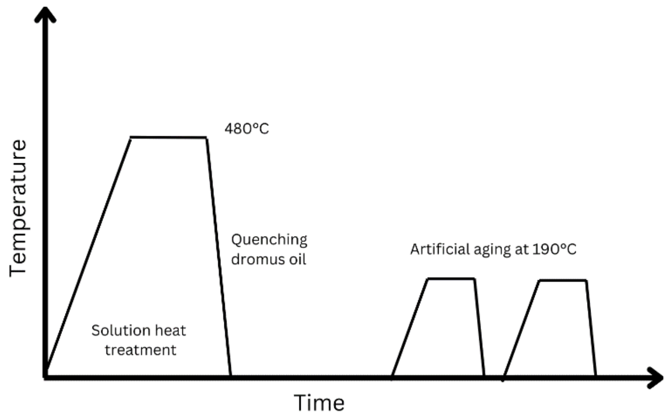


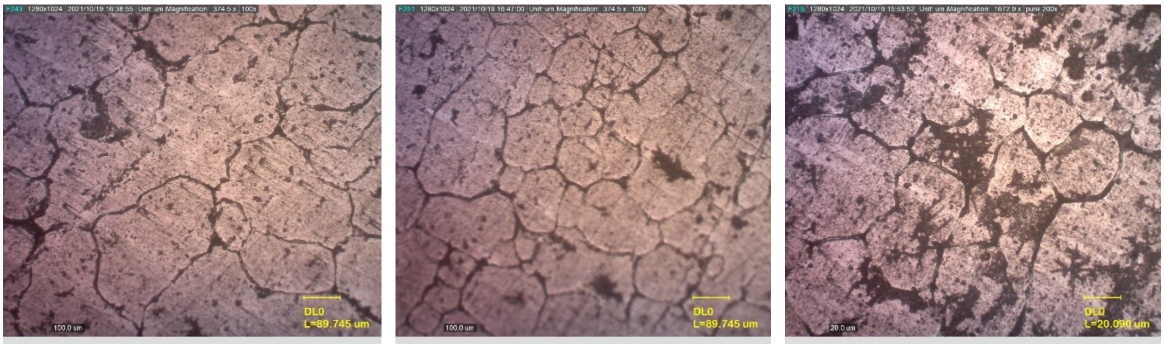
Figure 2. Two-step artificial aging heat treatment diagram

Figure 2 above shows the artificial aging heat treatment used in this study. The heat treatment begins with solution heat treatment, the specimen is heated to a temperature of 480°C, and held for 30 minutes. Furthermore, rapid cooling (quenching) uses dromus oil as a cooling medium. After the furnace returns to room temperature, the specimen is reheated to a temperature of 190°C, and held for several hours for the artificial aging process. The artificial aging process is repeated 2 times as depicted in Figure 2. This study uses variations in artificial aging holding time, namely 2 hours, 4 hours, and 6 hours as independent variables. The variation in holding times of 2 hours, 4 hours, and 6 hours during heat treatment is often chosen to study and optimize the effects of time on the material's properties. This variation is selected based on the following considerations: Shorter times (2 hours): Allow for initial microstructural changes, such as precipitation of strengthening phases, but might not fully optimize properties. Intermediate times (4 hours): Provide a balanced time to observe the progression of microstructural transformations. Longer times (6 hours): Explore whether prolonged holding leads to further improvement, stabilization, or potential degradation due to over-aging or grain growth. The times are often derived from the material's phase transformation kinetics, which depend on the diffusion rates of alloying elements like magnesium and silicon in Al6061 [11]. These durations ensure measurable changes in properties such as strength, hardness, and corrosion resistance. While the dependent variables used in this study are the microstructure and hardness number of Al6061.

3. RESULTS AND DISCUSSION

3.1 Microstructure of Al 6061 alloy resulting from artificial aging

The following are the results of testing the microstructure of Al6061 alloys resulting from artificial aging treatment.



(a) (b) (c)

Figure 3. Microstructure of Al6061 alloy after artificial aging treatment (a) 2 hours, (b) 4 hours, (c) 6 hours

Figure 3 presents the microstructure analysis of Al6061 alloy subjected to artificial aging treatment with varying holding times. The three images show a bright part, namely the Al matrix, and a dark part, namely Mg2Si deposits. Deposits or so-called precipitates are formed during the aging process. These deposits enhance the mechanical properties of the artificially aged Al6061 alloy. The following is a picture of the results of Image-J analysis to determine the percentage of Mg2Si in each variation.

Table 3. Grain size of Al6061 alloy resulting from artificial aging using ImageJ software.

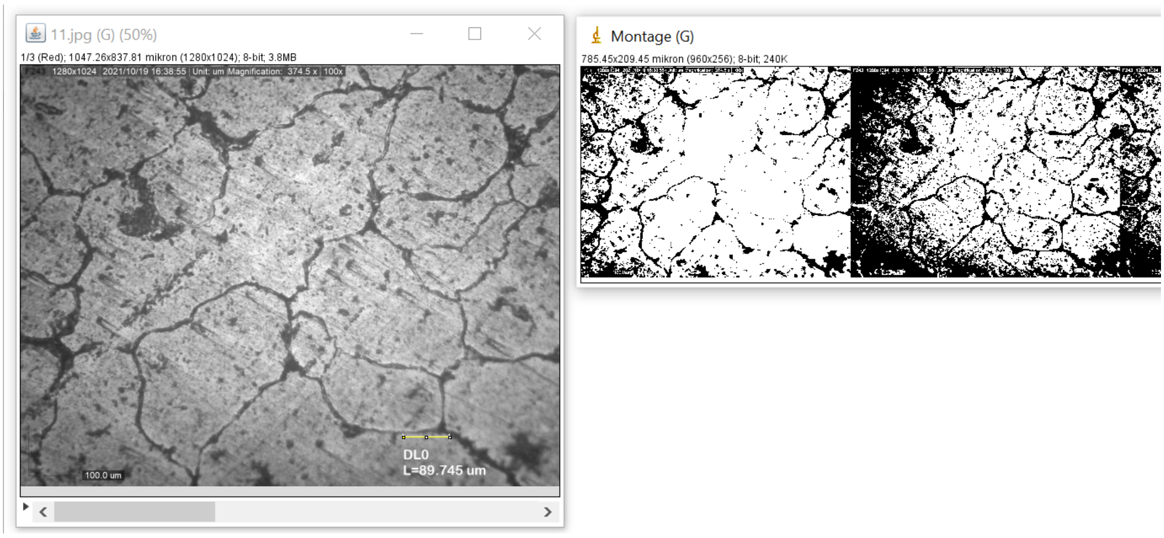
Treatment	Time holding (hour)	Grain diameter (μm)
Artificial aging	2	93.759
	4	47.633
	6	71.007

Figure 4 is the result of Image-J analysis of the microstructure test results of Al6061 alloy that has been treated with artificial aging with variations in holding time. The following is the percentage of β-Mg2Si phase in each variation of artificial aging.

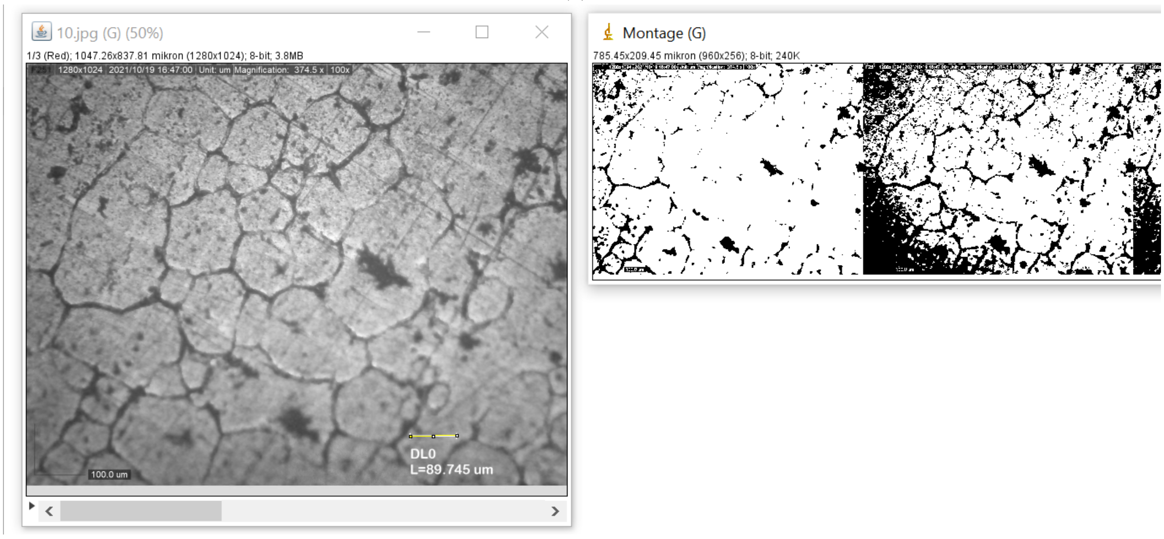
Table 4. Percentage of β-Mg2Si phase in Al6061 alloy resulting from artificial aging

Treatment	Holding time (hour)	Mg_2Si (%)
Artificial aging	2	19.752
	4	31.806
	6	29.002

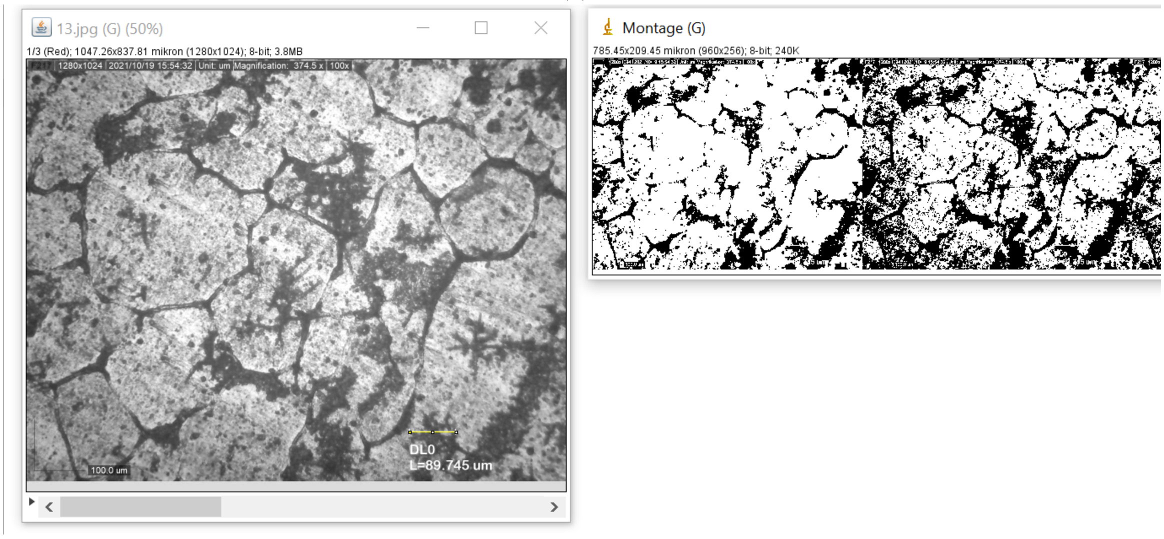
Based on Figure 4 and Table 3, the smallest grain size was obtained in the specimen with a variation of artificial aging holding time of 4 hours, while the largest grain size was obtained in the specimen with a variation of artificial aging holding time of 2 hours. Table 4 shows that the specimen with a variation of holding time of 4 hours has the highest β-Mg2Si phase of 31.806% and the α-Al phase of 68.194%. Meanwhile, the lowest percentage of β-Mg2Si phase was obtained in the specimen with a variation of holding time of 2 hours. The α-Al phase is shown in light color. The β-Mg2Si phase is shown in black, which is evenly visible on the grain boundaries, while the gray color is the Al-Fe-Si phase. A uniformly distributed β-Mg2Si phase can inhibit dislocation movement, thereby improving mechanical properties. The formation of Mg2Si intermetallic compounds can cause an increase in the mechanical properties of aluminum.



(a)



(b)



(c)

Figure 4. Image-J analysis results on Al6061 alloy after artificial aging treatment (a) 2 hours, (b) 4 hours, (c) 6 hours

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In Figure 3, it can be seen immediately that the grain size resulting from the artificial aging process with a holding time of 2 hours has a relatively large grain size. In the specimen resulting from the artificial aging process with a holding time of 6 hours, the grain size is not homogeneous, there are small grain sizes, but there are also some grains with quite large sizes. Meanwhile, in the specimen resulting from the artificial aging process with a holding time of 4 hours, the grain size is quite homogeneous, with a relatively small grain size. These results indicate that the peak condition occurs in the artificial aging process for 4 hours. This means that when the aging process is carried out for 2 hours to 4 hours, the specimen is in an underage condition, while when the aging process is carried out for 6 hours, the specimen is in an overage condition. This can occur because the aging process is too long, so that the dendrite structure recrystallizes and becomes smoother. As a result, the mechanical properties of Al6061 decrease again after aging for 6 hours. In this overage condition, the types of micro failures that often occur are failures near the interface between the particle and the matrix and failures in the matrix.

3.2 Hardness number of Al6061 alloy resulting from artificial aging

Figure 5 below shows the results of hardness tests on artificially aged Al6016 alloy. Based on Figure 5, the highest hardness was obtained in the specimen with artificial aging heat treatment on the specimen with a holding time variation of 4 hours, which is 110.8 HRE, while the lowest hardness was obtained in the specimen with a holding time variation of 2 hours, which is 98 HR_E. Meanwhile, the specimen with a holding time variation of 6 hours has a hardness value of 104.2 HR_E. The results of the hardness test are related to the results of the microstructure test, where the hardness value can be influenced by the grain size. The smaller the grain size, the higher the hardness number. Grain boundaries filled with Mg_2Si precipitates will increase the hardness of the material. Under 6-hour aging conditions, the Al6061 specimen experienced overaging, resulting in a decrease in hardness. The results of this study are almost the same as other studies related to the application of artificial aging on Al6061 alloys that experience overaging due to aging times that are too long, causing the material strength to decrease again.

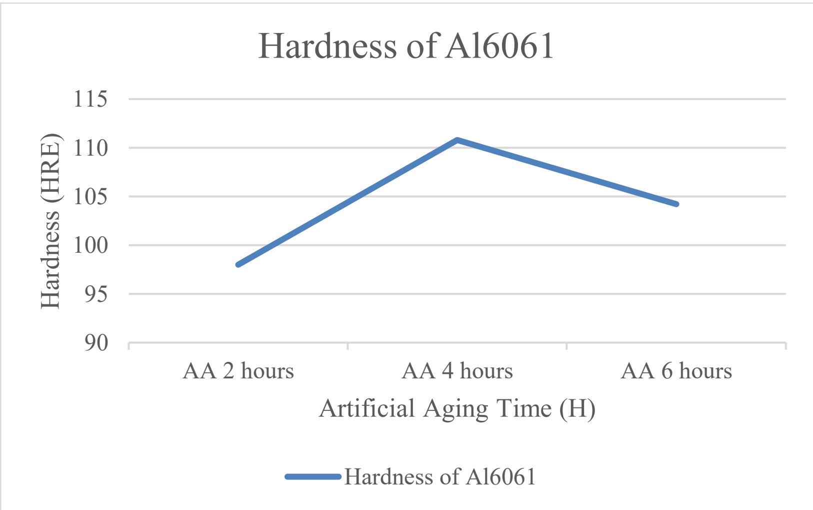

Figure 5. Hardness number of Al6061 alloy resulting from artificial aging

The potential application of studying the variation in holding times (2, 4, and 6 hours) during heat treatment of Al6061 alloy lies in optimizing its mechanical and physical properties for specific industries. Through the application of this heat treatment, not only is a material with increased hardness achieved, but also enhanced ductility.

4. CONCLUSION AND LIMITATION

This study demonstrates that artificial aging heat treatment enhances the mechanical properties of Al6061 alloy. According to the ImageJ analysis, the smallest grain diameter (47.633 µm) was observed in the specimen subjected to artificial aging for 4 hours. This occurs because this treatment is dominated by the α-Al phase and the low β-Mg2Si phase, which is 19.752%. These results are in line with the results of hardness testing, where the highest hardness value was obtained in the specimen with artificial aging treatment for 4 hours with a hardness value of 110.8 HRE. The specimen subjected to artificial aging for 6 hours experienced overaging, resulting in a lower hardness value.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Universitas Negeri Malang, Faculty of Vocational Studies, for providing the necessary facilities and support to carry out this research. We also thank the Department of Mechanical Engineering Technology for the resources and technical support during the experimental process. Special thanks are extended to our colleagues for their valuable input and assistance throughout this study. Finally, we appreciate the constructive feedback from reviewers, which significantly contributed to improving the quality of this paper.

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BIOGRAPHIES OF AUTHORS

Dewi 'Izzatus Tsamroh is a lecturer in the Diploma IV Manufacturing Engineering Technology at Universitas Negeri Malang, Indonesia. She received her Bachelor of Eduaction in Mechanical Engineering Education Program from Universitas Negeri Malang in 2017 and her M.Eng from the Universitas Negeri Malang, Malang, in 2019. She mainly researches materials science and engineering. She can be contacted at email: dewi.tsamroh.fv@um.ac.id

Dewi Puspitasari is a lecturer in the Department of Mechanical Engineering at Universitas Negeri Surabaya, Indonesia. She received her BSc in Mechanical Engineering from the Universitas Negeri Malang in 2016 and her M.Sc from the University Technologi PETRONAS, Malaysia, in 2019. She mainly researches materials science and engineering. She can be contacted at email: dewipuspitasari@unesa.ac.id.

Poppy Puspitasari is a Mechanical and Industrial Engineering Department lecturer at Universitas Negeri Surabaya, Indonesia. She received her BSc in Mechanical Engineering from the Universitas Negeri Malang in 2001, her M.Sc from the Bandung Institute of Technology (ITB), Indonesia in 2007 and her P.hD Electrical and Electronic Engineering. She mainly researches in nanomaterial. She can be contacted at email. poppy@um.ac.id