SEMARAK ILMU PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Effect of Heat Treatment on Mechanical Characteristics and Microstructure of Aluminium Alloy AA6061

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ARTICLE INFO

Article history:
Received 23 July 2024
Received in revised form 26 October 2024
Accepted 8 November 2024
Available online 20 November 2024

ABSTRACT

Aluminium alloy 6061 (AA6061) is widely used across various industries. It has untapped potential in diverse sectors due to its exceptional strength, lightweight characteristics and corrosion resistance. It finds value in aerospace, automotive, marine, sports gear, architecture, renewable energy, electronics, healthcare devices, packaging and defence. This study investigates the impact of heat treatment on AA6061 on its microstructural and mechanical properties (tensile strength and microhardness). The main goals of this study involve assessing the mechanical properties of AA6061 after subjecting it to solution heat treatment at various temperatures and time intervals. Furthermore, the study aims to understand the relationship between microstructural alterations and mechanical properties in AA6061 following heat treatment. A combination of tensile tests, hardness tests, and scanning electron microscopy (SEM) to examine the material's microstructure. The findings reveal that the sample subjected to the heat treatment of 450°C for 60 minutes exhibited the highest tensile strength, boasting an impressive 130.9 MPa, coupled with a remarkable hardness of 19.8 HRB. Conversely, the sample treated at 550°C for 60 minutes displayed the most significant elongation percentage, reaching a remarkable 46%. These results can be explained by analysing the microstructure. Finer grain boundaries led to increased tensile strength and hardness, while a larger dendritic microstructure was linked with lower tensile strength and hardness. Remarkably, the second one led to higher elongation percentages. Therefore, precise control of the heating temperature and duration is crucial to enhance the performance of aluminium alloy, AA6061. With continuous research, alloy improvement and creative design, AA6061 have the potential to enhance performance and efficiency in these areas, driving technological advancements and better products.

Keywords:
Heat treatment; mechanical characteristics; microstructure; aluminium alloy AA6061

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https://doi.org/10.37934/arfmts.124.1.209219

1. Introduction

Aluminum alloys, which combine aluminum with elements like copper, magnesium, silicon, manganese, or zinc, have become increasingly important for their role in creating lightweight, high-strength structural and engine components. This development is driven by the need to reduce fuel consumption and combat carbon emissions, making aluminum alloys, the second most abundant material globally after steel, a promising solution. These alloys are classified into seven series, each with specific properties and applications. AA6061-T6 is a precipitation-hardened alloy containing aluminum, magnesium, and silicon, belongs to the 6XXX series. It is highly regarded for its exceptional workability, strong mechanical properties and resistance to corrosion. This alloy is commonly utilized in aircraft components and construction projects.

Khoshroyan and Darvazi [1] investigate how the temperature, stress and distortion evolve during the MIG welding of Al6061-T6 plates. The factors such as material properties, welding speed and welding sequence, were considered. The findings indicated that higher welding speed reduced certain types of distortion but increased maximum stress levels. Moreover, increasing the welding current amplified both stress and deformation. Remarkably, altering the welding sequence had a more pronounced effect on distortion distribution compared to stress distribution [1].

Friction Stir Welding (FSW) of 2014 Aluminum alloy, which is widely used in industries like aerospace and automotive has been used together with cryogenic cooling by Chandana *et al.,* [2]. Cryogenic cooling is able to reduce the grain size and improve the mechanical properties. The study also found that using this cooling method resulted in smaller grain sizes (2-4 micrometers on average) and superior mechanical properties. The specific welding parameters, including a 24mm tool shoulder diameter, a tapered cylindrical thread pin profile, a rotational speed of 900 rpm, and a welding speed of 60 mm/min, which produced equiaxed grains are the best outcomes. The Vickers hardness testing and scanning electron microscopy (SEM) highlighting the significant enhancements in mechanical properties due to cryogenic cooling [2]. Singh *et al.,* [3] examined how cryogenic cooling affects the mechanical properties and microstructure of AA6061-T6. The results show an increase in hardness and tensile strength.

A non-heat treatable aluminum alloys, categorized as 3xxx, 4xxx, 5xxx, and 1xxx series, comprising elements like manganese (Mn), silicon (Si), magnesium (Mg), and pure aluminum have been explored by Haque *et al.,* [4]. These alloys gain strength through solid solution strengthening and strain hardening. Four NHT aluminum alloys were created and studied, assessing microhardness and thermal conductivity after different annealing processes. The results show that by adding Mg may increase the microhardness but reduce the thermal conductivity due to brittle intermetallic compounds. Si minimally affected hardness, while Mn had some improvement. Mg-added alloys softened faster during annealing and thermal conductivity decreased with alloying. Various microstructures were observed, including compact (pure Al), elongated grains (Mn), and Si eutectic phases. Mg addition led to lower thermal conductivity and stress corrosion cracking. Higher annealing temperatures resulted in recrystallization.

Alloy composition, microstructure and processing methods are crucial mechanical properties of Aluminium Alloy AA6061. These properties encompass a Tensile Strength range of 110-310 MPa, which depends on heat treatment conditions and processing techniques, a Hardness that varies from 40-95 HB, indicating its resistance to indentation and abrasion, a Ductility typically ranging from 5-15%, impacting its ability to withstand deformation without fracturing, a Yield Strength that varies between 25-500 MPa, influenced by the temperature and duration of the heat treatment process, and a Young's Modulus that ranges from 68 GPa to 72 GPa, reflecting the material's resistance to deformation when subjected to stress [5-7].

The duration of artificial aging significantly influences AA6061. Longer heating periods yield larger and more evenly spread precipitates, enhancing strength and hardness. However, excessive heating can lead to over-aging, negatively impacting mechanical properties, including ductility and hardness [8].

Studies have demonstrated that optimizing solution heat treatment time and temperature can significantly enhance the quality and morphology of alloys. For instance, a high-temperature solution heat treatment at 510°C improved the quality index and elongation performance of A356 DC alloy [9]. Adjusting solution treatment temperature and time can enhance both Ultimate Tensile Strength (UTS) and Yield Strength (YS) [10]. Higher aging temperatures accelerate the precipitation of the strengthening phase within the aluminum matrix, increasing the material's strength and hardness [11]. The cooling rate during heat treatment plays a crucial role in determining microstructure and mechanical properties. Faster cooling rates lead to finer grains and enhanced properties, including increased Ultimate Tensile Strength (UTS) and Yield Strength (YS) [12]. Furthermore, varying the cooling rate can significantly affect grain size, secondary phase width, and crystalline phase size, thereby influencing mechanical properties [13]. Salleh *et al.,* [14] found the optimal T6 treatment involved heating at 530°C for 30 minutes and ageing at 180°C for 2 hours, which significantly improved the alloy's tensile strength (252.3 MPa), hardness (98.9 HV), and reduced its friction coefficient (0.4299).

The need for a better understanding of how heat treatment affects AA6061, a widely used alloy has been addressed in this research. Currently, there's no consensus on this, which makes it challenging to choose the right alloy for specific applications and processes, potentially increasing costs. The study has two main objectives: first, to assess AA6061's mechanical properties after various heat treatments using hardness and tensile tests, and second, to examine how heat treatment changes its microstructure and how this relates to mechanical properties. Ultimately, this research aims to unlock AA6061's potential, providing valuable insights for cost-effective decision-making in various applications and manufacturing methods.

2. Methodology

Sample preparation, heat treatment, and the subsequent characterization methods customized specifically for AA6061 will be discussed in this section.

A total of 14 pieces of Aluminum alloy grade AA6061 were prepared. Seven of these were specifically designed for tensile testing and the remaining seven pieces were crafted into dimensions measuring 15mm x 15mm for subsequent scanning electron microscopy analysis as shown in Figure 1. The heat treatment procedure for AA6061 entails subjecting the material to varying temperatures and durations, followed by gradual cooling to room temperature. The specific temperature and heating duration combinations are presented in Table 1. The mechanical properties and microstructure of AA6061 depend primarily on the heat treatment temperature and duration. These factors have a notable impact on tensile strength, elongation percentage, ductility, hardness and microstructure features.

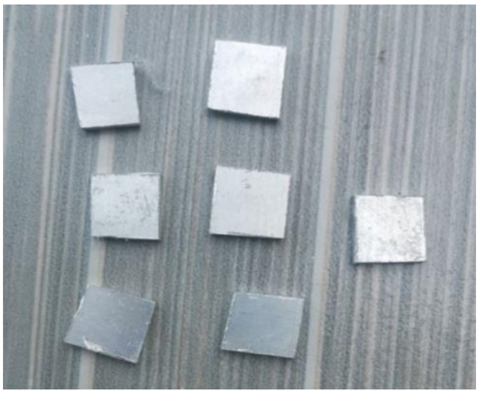


Fig. 1. Specimens following the SEM sectioning process

Table 1
The temperature and duration of heating applied to the samples

Samples	1	2	3	4	5	6	7
Temperature (°C)	-	450	450	500	500	550	550
Time (mins)	-	30	60	30	60	30	60

The dimensions and geometry of the tensile test specimens can be found in Figure 2 and Table 2.

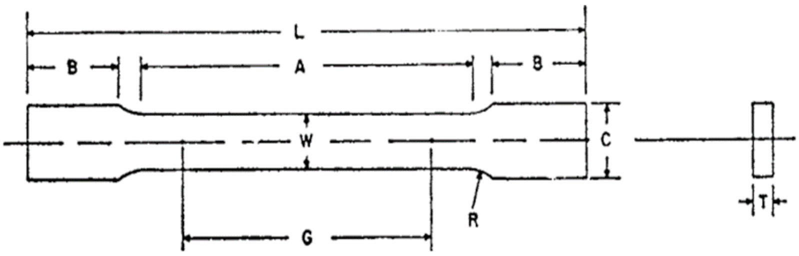


Fig. 2. Geometry of tensile test specimen

Table 2
Dimensions of tensile test specimens

Dimensions in mm	
G-Gauge Length	50
W-Width	12.5
T-Thickness	3
R-Radius of fillet	12.5
L-Overall length	200
A-Length of reduced section	57
B-Length of grip section	50
C-Width of grip section	20

The AA6061 plate underwent precision cutting (Figure 3), aligning with the specifications outlined in the American Society for Testing and Materials, ASTM E* standard. These precise dimensions were tailored for tensile testing employing the Zwick Roell Universal Testing Machine (ASTM E8) and for microhardness testing using the Zwick Roell Universal Hardness Tester (ASTM E18-22). Conversely, in order to ready the samples for SEM analysis, a series of steps was undertaken. Initially, they were subjected to grinding, followed by a polishing phase, and finishing with an etching process illustrated in Figure 4. Etching before SEM examination is essential to clean the sample surface, reveal important structural details, and enhance image quality for better analysis.

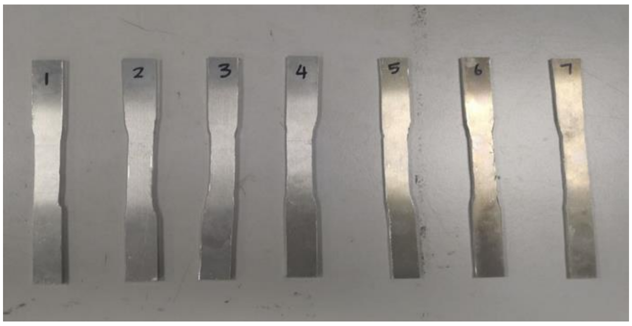


Fig. 3. Samples post-cutting for tensile testing

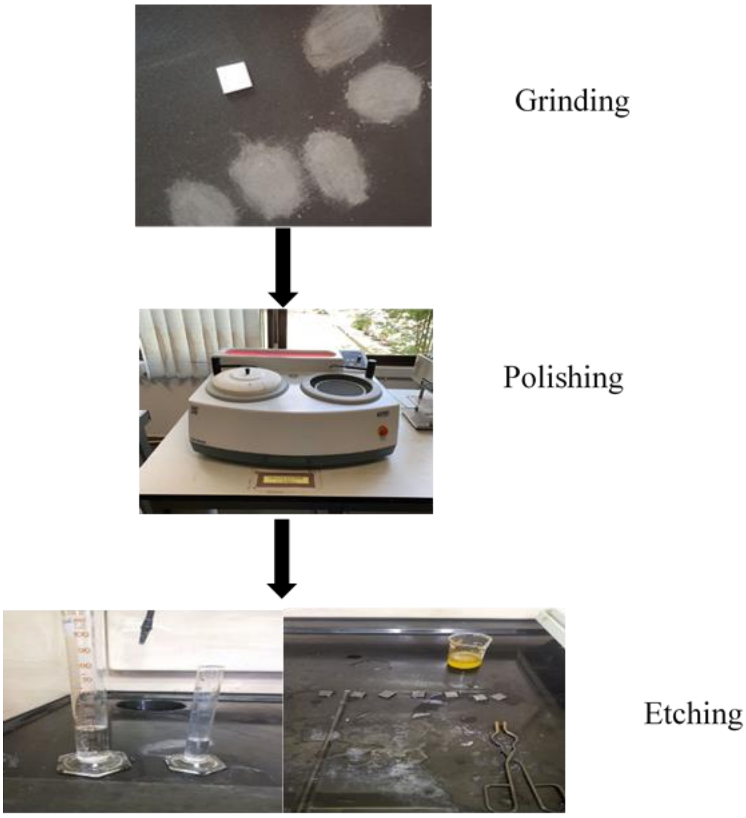


Fig. 4. Samples going through grinding, followed by polishing, and an etching stage prior to scanning electron microscopy examination

3. Results

3.1 Mechanical Properties and Microstructure

The impacts of heat treatment to mechanical properties and microstructure of AA6061 aluminium alloy will be discussed in this section. The correlation between heat treatment processes, mechanical properties and its microstructure of AA6061 aluminium alloy will be explored.

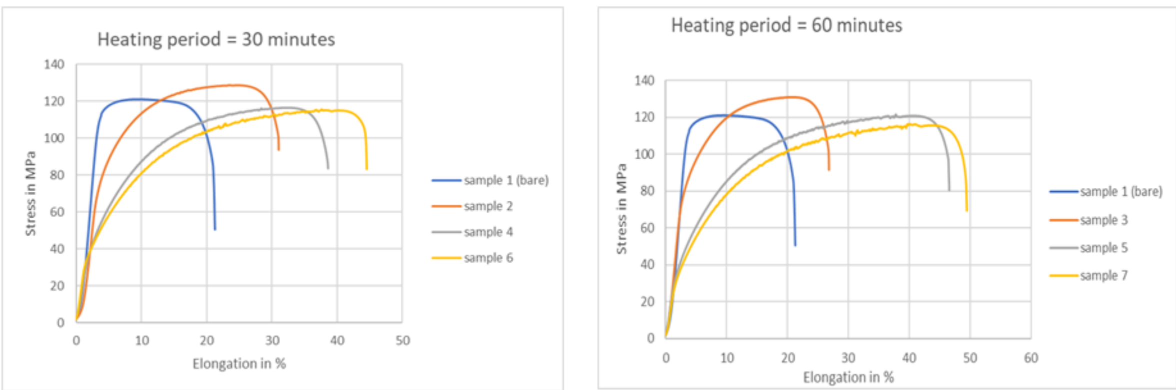
3.1.1 Tensile strength

In Figure 5(a), the elongation percentages for various samples, including an untreated reference sample and one that underwent a heat treatment process at 500°C for 30 minutes, referred to as sample 6 are presented. Notably, the untreated sample 1 exhibited the lowest elongation percentage, while sample 6 demonstrated the highest at 42% prior to fracture. It's worth mentioning that the tensile strength of the untreated Aluminium Alloy is 115 MPa and 131-133 MPa, respectively [15,16]. It is interesting to observe that the increased elongation in sample 6 comes at the expense of reduced tensile strength, measuring at 115.7 MPa, in contrast to the other samples. This behaviour can be attributed to microstructural changes induced by the heat treatment process, commonly known as annealing.

Sample 6 displays increased elongation but possesses lower tensile strength after annealing processes. Annealing serves to relax the alloy's microstructure, alleviating internal stresses and enhancing ductility. Consequently, it exhibits greater elongation due to improved ductility by allowing it to deform further before reaching the breaking point. Conversely, the decrease in sample 6's tensile strength might be due to the annealing process too Annealing rearranges dislocations within the crystal lattice, facilitating material deformation and elongation, which typically trades strength for ductility.

Heating initially enhances the AA6061 alloy's tensile strength through precipitation hardening, a process in which specific elements form small precipitates that strengthen the material. However, at higher temperatures, these precipitates tend to average out, leading to a reduction in tensile strength. Conversely, higher temperatures improve the alloy's ductility, allowing it to stretch more before breaking. This accounts for the rise in elongation percentage with increasing temperature. Remarkably, the optimal balance between strengthening and ductility is achieved at 450°C (sample 2), making it the ideal temperature for maximizing the alloy's mechanical properties.

Figure 5(b) shows the stress-elongation percentage graph for a 60-minute (Figure 5(b)) and the heating duration provides valuable insights into the microstructural alterations and mechanical behavior of the AA6061 alloy. Sample 7, exposed to a temperature of 550°C, demonstrated the highest elongation percentage, reaching 46%. It highlights the notion that elevated heating temperatures can enhance AA6061's ductility by instigating microstructural changes that promote dislocation mobility and grain boundary motion.



(a) (b)

Fig. 5. Stress against elongation percentage for heating period of (a) 30 minutes and (b) 60 minutes

An elongation percentage of 43% and tensile strength of 121.6 MPa have been observed in sample 5. This could be attributed to the inherent trade-off between ductility and tensile strength. Whereas, sample 3 exhibited the highest tensile strength (130.92 MPa), primarily attributable to the formation of fine precipitates within the microstructure, which hinder dislocation movement. Nonetheless, this increase in strength is accompanied by a decrease in ductility, resulting in an elongation percentage of roughly 23%.

Comparatively, sample 2, heated at 450°C for 30 minutes, exhibited superior ductility compared to sample 3 due to the absence of over-aging effects. It is worth noting that extending the heating duration from 30 to 60 minutes at temperatures of 500°C and 550°C resulted in an increase of both tensile strength and ductility for AA6061. At 500°C, tensile strength increased from 116.5 MPa to 121.6 MPa, while at 550°C, it rose from 115.7 MPa to 116.4 MPa, accompanied by a boost in elongation percentage from 42% to 46%.

3.1.2 Microhardness

In order to assess the hardness of AA6061 samples following the heat treatment, a Rockwell Hardness test using the B scale was performed. For each sample, three hardness measurements were recorded, and the average hardness value was subsequently computed as shown in Table 3.

Table 3
Average Rockwell hardness

Sample	Hardness, HRB			Average Hardness, HRB
	Reading 1	Reading 2	Reading 3	
1	18.90	15.20	18.80	17.63
2	17.30	16.90	19.90	18.03
3	20.50	20.60	18.60	19.80
4	16.80	15.30	20.2	17.37
5	13.50	19.40	20.20	17.70
6	17.10	15.40	17.60	16.70
7	19.60	18.40	13.80	17.27

As shown in Table 3, Figure 6 illustrates the relationship between average Rockwell Hardness and heating temperature. It's worth noting that the graph demonstrates a clear inverse linear correlation for both the 30-minute and 60-minute heating durations. In both series, samples exposed to 450°C exhibited the highest levels of hardness, measuring 19.8 HRB and 18.03 HRB, surpassing the hardness of the untreated base sample, which recorded 17.63 HRB. This increase in hardness is attributed to the presence of precipitates within AA6061, which contribute to strengthening by obstructing dislocation movement.

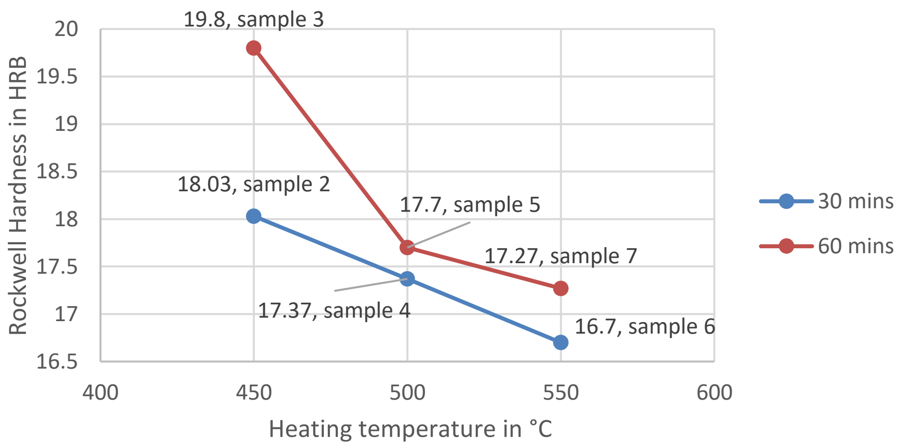


Fig. 6. Rockwell hardness against heating temperature

The hardening effect is particularly noticeable when the precipitates are smaller in size, as indicated in a study by Qi *et al.,* [17]. Additionally, AA6061 samples that underwent a 60-minute heating period demonstrated greater hardness compared to those heated for 30 minutes. Interestingly, three samples (sample 4, sample 6, and sample 7) exhibited hardness values lower than that of the untreated base sample.

Referring to the data in Table 4, the relationship between tensile strength and hardness has been plotted (Figure 7). Figure 7 reveals a clear and directly proportional connection between tensile strength and hardness. When AA6061 exhibits its lowest recorded hardness of 16.7 HRB, its tensile strength stands at its lowest, measuring 115.7 MPa. Conversely, when it reaches the highest recorded hardness of 19.8 HRB, its tensile strength reaches its peak at 130.9 MPa. This highest tensile strength surpasses that of the untreated base sample by 9.8 MPa. It's important to note that the relationship between tensile strength and hardness is inseparable, with higher hardness consistently corresponding to greater tensile strength.

Table 4
Average Rockwell hardness and tensile strength

Sample	Tensile Strength (MPa)	Average Hardness (HRB)
1	121.10	17.63
2	128.73	18.03
3	130.92	19.80
4	116.51	17.37
5	121.56	17.70
6	115.70	16.70
7	116.40	17.27

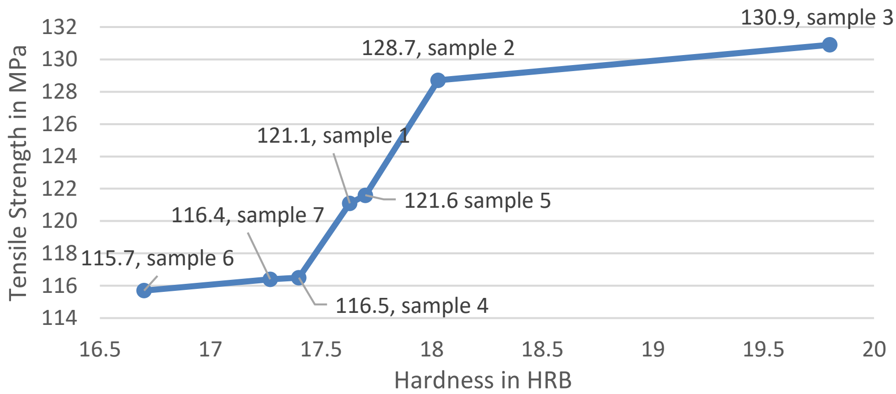
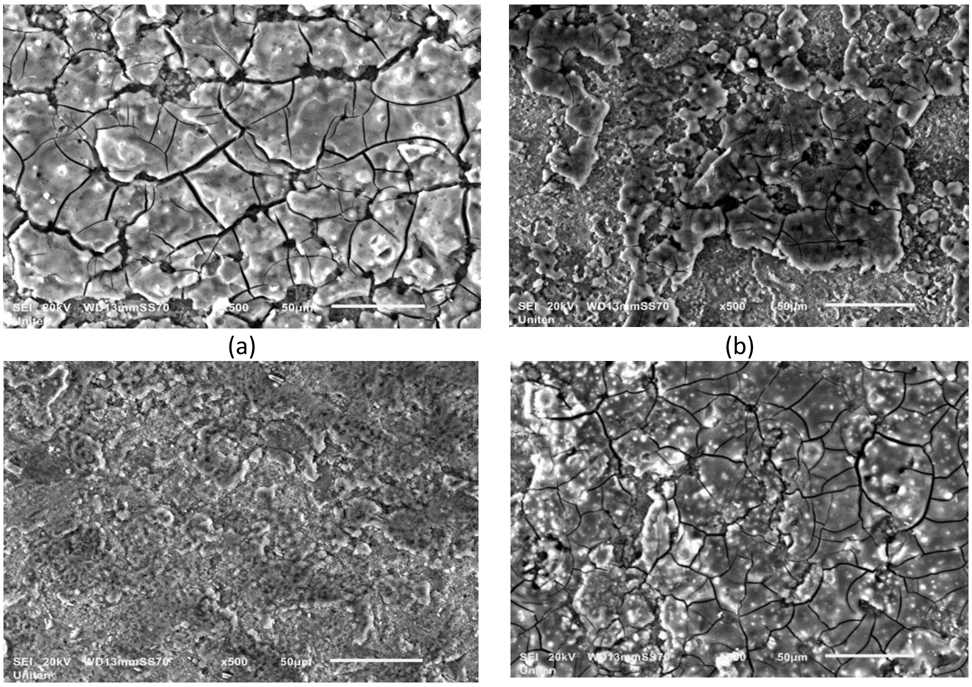


Fig. 7. Tensile strength against hardness

3.1.3 Microstructure examination

SEM microstructures of four unique samples: Sample 2, Sample 3, which demonstrated the highest tensile strength, and Samples 6 and 7, highlighting the highest elongation percentages have been shown in Figure 8.



(a) (b) (c) (d)

Fig. 8. SEM at magnification of x500 (a) Sample 2, (b) Sample 3, (c) Sample 6, (d) Sample 7

Upon analysing the SEM images of sample 2, it becomes clear that the grain boundaries within AA6061 are readily noticeable. It's worth highlighting that, in sample 2, these grain boundaries appear more pronounced when compared to sample 3. Conversely, in sample 3, the grain boundaries are notably finer than those seen in sample 2, providing insights into the higher tensile strength observed in sample 3. Essentially, the size and visibility of these grain boundaries have a substantial impact on influencing the mechanical properties, especially tensile strength.

The microstructures of both samples 6 and 7 exhibited notable similarities, reflecting the minimal variation in their mechanical properties. In both cases, the presence of a larger dendritic structure within their microstructures was evident. This dendritic structure is a well-documented outcome of the solidification process, as referenced by Selvam *et al.,* [18]. Supercooling plays an important role in forming the dendritic pattern during solidification process. The structure consists of elongated primary α-Al dendritic arms, characterized by their high aspect ratio. Interestingly, the formation of these larger, distinct dendritic microstructures contributes to a higher elongation percentage but lower tensile strength and hardness.

4. Conclusions

The optimal heating conditions for achieving peak tensile strength is 450°C for a 60-minute heating period has been found. In addition, the highest ductility was obtained by heating the samples to 550°C for 60 minutes. Heat treatment appears as an important process in tailoring the mechanical attributes and microstructure of AA6061 aluminium alloy. Remarkable enhancements in the alloy's performance can be realized through precise control of heating temperature and duration. In terms of mechanical properties, heat-treated AA6061 exhibits superior strength and hardness compared to untreated sample. However, achieving elevated strength while maintaining acceptable levels of ductility and toughness requires a careful balance. This highlights the need for a fine balance on the heat treatment parameters to optimize the performance of AA6061 aluminium alloy.

Acknowledgement
This research was funded by internal grant from Universiti Tenaga Nasional, Malaysia (BOLD Grant 2023 J510050962).

References

[1] Khoshroyan, Amirreza, and Armin Rahmati Darvazi. "Effects of welding parameters and welding sequence on residual stress and distortion in Al6061-T6 aluminum alloy for T-shaped welded joint." *Transactions of Nonferrous Metals Society of China* 30, no. 1 (2020): 76-89. https://doi.org/10.1016/S1003-6326(19)65181-2

[2] Chandana, Ragunam, Bollapally Swarnalatha, Bollepelly Manichandra, and Aruri Devaraju. "Study on the Effect of Cryogenic Cooling on Microstructure and Mechanical Properties of Friction Stir Welded 2014 Aluminium Alloy." *International Journal of Pure and Applied Mathematics* 118, no. 24 (2018).

[3] Singh, S. Prathap, D. X. Tittu George, A. Anitto Joe Xavier, and G. Abinicks Raja. "Effect of heat treatment on the hardness behaviour of the aluminium 6061 alloy." *Materials Today: Proceedings* (2023).

[4] Haque, Mohammad Salman, SM Nasim Rokon, and Mohammad Salim Kaiser. "Strengthening and softening behavior of non-heat-treatable aluminum alloys subject to deformation and annealing treatment." *Materials Today: Proceedings* 82 (2023): 151-157. https://doi.org/10.1016/j.matpr.2022.12.113

[5] Monica, V., G. Lakshmikanth, S. Lathicashree, N. Senthilkumar, A. Muniappan, and B. Deepanraj. "An experimental analysis and optimization of heat treatment parameters of Al6061 alloy for improved mechanical properties." *International Journal of Mechanical and Production Engineering Research and Development* 9, no. Special Issue (2019): 46-59.

[6] Chauhan, Krishna Pal Singh. "Influence of heat treatment on the mechanical properties of aluminium alloys (6xxx series): A literature review." *International Journal of Engineering Research & Technology (IJERT)* 6, no. 03 (2017): 386-389. https://doi.org/10.17577/IJERTV6IS030301

[7] Georgantzia, Evangelia, Michaela Gkantou, and George S. Kamaris. "Aluminium alloys as structural material: A review of research." *Engineering Structures* 227 (2021): 111372. https://doi.org/10.1016/j.engstruct.2020.111372

[8] Budiarto, Budiarto, Susilo Susilo, and Ulung Sanjaya. "The effect of artificial age time on crystal size, dislocation density, hardness and micro structure on Al 6061 materials alloy." In *AIP Conference Proceedings*, vol. 2342, no. 1. AIP Publishing, 2021. https://doi.org/10.1063/5.0045373

[9] Yasin, M. R. Mohamad, and S. N. A. Abdul Razak. "Effect of high temperature solution heat treatment time on quality index and morphology of A356 DC alloy." *Materials Today: Proceedings* 48 (2022): 1924-1928. https://doi.org/10.1016/j.matpr.2021.09.477

[10] Kang, Ho-jung, Ho-sung Jang, Seong-hyo Oh, Pil-hwan Yoon, Gyu-heun Lee, Jin-young Park, Eok-soo Kim, and Yoon-suk Choi. "Effects of solution treatment temperature and time on the porosities and mechanical properties of vacuum die-casted and T6 heat-treated Al-Si-Mg alloy." *Vacuum* 193 (2021): 110536. https://doi.org/10.1016/j.vacuum.2021.110536

[11] Kumar, Mukesh, Muhammad Moazam Baloch, Muhammad Ishaque Abro, Sikandar Ali Memon, and Ali Dad Chandio. "Effect of artificial aging temperature on mechanical properties of 6061 aluminum alloy." *Mehran University Research Journal of Engineering & Technology* 38, no. 1 (2019): 31-36. https://doi.org/10.22581/muet1982.1901.03

[12] Jiang, Haiyang, Fuqing Jiang, Bijun Xie, Bing Wang, Bin Xu, Xu Hu, Liang Xu et al. "Effects of the cooling rate on mechanical properties and microstructure of near-α Ti-6Al-3Zr-2Nb-Mo alloy." *Materials Characterization* 195 (2023): 112529. https://doi.org/10.1016/j.matchar.2022.112529

[13] Lu, Bing, Yong Li, Haiyao Wang, Yin Wang, Wei Yu, Zhaodong Wang, and Guangming Xu. "Effects of cooling rates on the solidification behavior, microstructural evolution and mechanical properties of Al-Zn-Mg-Cu alloys." *Journal of Materials Research and Technology* 22 (2023): 2532-2548. https://doi.org/10.1016/j.jmrt.2022.12.082

[14] Salleh, Mohd Shukor, Hanizam Hashim, Mohd Zaidi Omar, Abu Bakar Sulong, Soufhwee Abd Rahman, Saifudin Hafiz Yahaya, Mohd Warikh Abd Rashid, and Salah Al-Zubaidi. "T6 heat treatment optimization of thixoformed LM4 aluminium alloy using response surface methodology." *Malaysian Journal on Composites Science and Manufacturing* 3, no. 1 (2020): 1-13. https://doi.org/10.37934/mjcsm.3.1.113

[15] Kareem, Ansar, Jaber Abu Qudeiri, Asarudheen Abdudeen, Thanveer Ahammed, and Aiman Ziout. "A review on AA 6061 metal matrix composites produced by stir casting." *Materials* 14, no. 1 (2021): 175. https://doi.org/10.3390/ma14010175

[16] Henan Wealthall International Trading. "Mill Certificate AA6061-O (Aluminium Alloy Coil & Sheet)." *Henan Wealthall International Trading Co. Ltd, Zhengzhou City, China*, 2022.

[17] Qi, Zewu, Baoqiang Cong, Bojin Qi, Gang Zhao, and Jialuo Ding. "Properties of wire+ arc additively manufactured 2024 aluminum alloy with different solution treatment temperature." *Materials Letters* 230 (2018): 275-278. https://doi.org/10.1016/j.matlet.2018.07.144

[18] Selvam, J. David Raja, D. S. Robinson Smart, and I. Dinaharan. "Microstructure and some mechanical properties of fly ash particulate reinforced AA6061 aluminum alloy composites prepared by compocasting." *Materials & Design* 49 (2013): 28-34. https://doi.org/10.1016/j.matdes.2013.01.053