EFFECT OF HEAT TREATMENT ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF 6061 ALUMINUM ALLOY

J. Ridhwan[1*], J. A. Noor[1], M. S. Zakaria[1], Z. Zulfattah[1], M. H. M. Hafidzal[1]

[1]Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, Durian Tunggal, Melaka, Malaysia

ABSTRACT

The objective of this study was to illustrate the effect of various cooling rate and precipitation hardening on microstructure and mechanical properties of 6061 aluminum alloy. Samples were solution treated at 400°C before cooling in furnace, air, and water quench. Precipitation hardening was conducted by solution treating samples at 530°C followed by water quench and reheating at 100°C and 200°C. It was observed that the fast cooling rate on quenched sample produced finer grain and higher strength while slow cooling rates on annealed sample produced coarser grain and lower tensile strength. Longer precipitation hardening time resulted in larger precipitates size which led to drop in strength (over aged). Meanwhile, higher temperature resulted in shorter time to reach over aging. Precipitation hardening at 100°C for seven hours had successfully increased the UTS by 95.9% to 625 MPa due to formation of finely dispersed precipitates. Meanwhile, annealing had lowered the UTS by 62% to 197 MPa due to formation of coarser grain.

***KEYWORDS**: 6061 Aluminum alloy; Heat treatment; Precipitation hardening; Quenching*

1.0 INTRODUCTION

Aluminum is one of the major elements on earth. It is an important material in the modern world over steel. Aluminum alloys are widely used in engineering structures and components where light weight or corrosion resistance is required (Budinski, 2002). The example of the structures that made up from aluminum is aircraft body, ferries, missiles, satellites, automobile component, and many more. This alloy combines properties from several alloying elements such as magnesium and silicon in order to achieve a good balance of corrosion resistance, strength, machinability and price. In this study, Aluminum alloy 6061

* Corresponding author email: ridhwan@utem.edu.my

was chosen to undergo various heat treatment processes in order to improve its properties. This specific alloy was chosen because of its wide range of applications and well known properties.

Heat treatment is a series of operations involving the heating and cooling of metals in the solid state. Its purpose is to change a mechanical property or combination of mechanical properties so that the metal will be more useful, serviceable, and safe for a definite purpose. By heat treating, a metal can be made harder, stronger, and more resistant to impact. On the other hand, heat treating can also make a metal softer and more ductile.

Annealing is a process where aluminum alloy is heated to a certain temperature in order to reverse the effects of work hardening whereby an annealing process is to soften the material. The solution heat treatment temperature is set above the recrystallization temperature which means that the grains will begin to grow again. This temperature is a direct result of the amount of strain and residual stress in the material prior to annealing (Kelley et al., 2012).

Solutionizing aluminum allows for the maximum amount of solute to form in the solid metal, greatly increasing the amount of precipitates. This is accomplished by heating the material to just below the eutectic melting temperature and leaving it for a predetermined amount of time. Keeping the temperature in check is vital to the outcome of the solutionizing process. Overheating will raise the temperature above the eutectic point causing localized melting and a reduction in material property values (Kelley et al., 2012). Under heating may not let all of the solutes grow into the solid solution, leaving fewer precipitates for future treatments (Totten et al., 2003).

Quenching is an important part of the heat treatment process. The process involves cooling the material after heat treatment in various mediums and various speeds. There are both rapid and slow quenches, and different quenching fluids (Kelley et al., 2012). The purpose of this process is to stop precipitation growth and preserve the metal in its current state immediately after heat treated. By cooling off the material, the higher temperatures cannot continue to have an effect on the material properties past the designated heating time (Totten et al., 2003).

A previous study has shown that precipitation hardening could increase the microhardness of 6061 aluminum alloy where higher hardness was recorded at a longer aging time until it reached a peak aging condition

(Rezaei et al., 2010). Another study conducted by Mansourinejad et al., (2012) has shown that double aging treatment resulted to lower the strength of material as compared with single age. Tan and Muhammad (2009) showed that aging at higher temperature resulted to drop in material's strength as the aging time increased. In addition, at higher aging temperature, shorter time is required to reach peak aging (Tan & Muhammad, 2009).

Heat treatment of aluminum alloy is one alternative method that can be used in order to increase the strength of material without further alloying. Although there are previous studies that had been conducted on this particular material, there are certain temperature range and time that had not been discovered yet which might be able to further increase its strength, hence, this study is intended to apply various types of heat treatment on this material in order to study the effect of cooling rate and aging temperature on the strength and microstructure of 6061 aluminum alloy.

2.0 MATERIALS AND METHODOLOGY

In this study, 6061 aluminum alloy rod with 19 mm diameter were used. The aluminum rods were cut by using bend saw machine into five mm of thickness. The composition of as received material was analyzed by using Energy Dispersive X-Ray Analysis (EDX).

2.1 Heat Treatment

The heat treatment process involved in this research was solution heat treating, normalizing, annealing, quenching, and precipitation hardening.

For normalizing, annealing and quenching process, the samples were prior solution treated in the furnace for two hours at 400oC before undergoing the cooling process. Normalized, annealed, and quenched samples was cooled at room, furnace, and water quenched respectively after solution treating.

For precipitating hardening, samples were prior heat treated for two hours at 530^{o}C before quickly quenched in fresh water. Quenched samples were further aged at 100^{o}C and 200^{o}C for 0.5, 1, 2, 4, and 7 hours for precipitation hardening to occur. In this process, samples were aged in order to identify the effect of different temperature and time on microstructures and the strength of 6061 Aluminum Alloy.

2.2 Mechanical Testing and Microstructure Investigation

Investigation involved in the heat treated samples were tensile test and microstructure investigation. Tensile test was conducted by using Instron Universal Tensile Machine where the size of the specimen was fabricated according to ASTM E8 standard. For microstructure investigation, the sample was mounted, grinded, and polished until the mirror surface was obtained. Keller's solution was used as an etching solution in order to reveal the microstructure. The inverted optical microscope was used to investigate the microstructural change after heat treatment.

3.0 RESULTS AND DISCUSSION

3.1 Composition and Tensile Strength of As-Received Material

The composition of as received material obtained from EDX was shown in Table 1. This finding is consistent with Micheal et al., (2010).

Table 1. Composition for 6061 aluminum alloy by EDX analysis

Element	Weight %	Atomic %
Al	97.14	97.68
Mg	1.09	1.22
Si	0.54	0.53
Cr	0.21	0.11
Mn	0.24	0.12
Fe	0.35	0.17
Cu	0.16	0.07
Zn	0.26	0.11
Total	**100**	**100**

Prior to heat treatment of materials, tensile test and hardness test was conducted on as-received specimen. The experimental value of hardness, ultimate tensile strength and yield strength were shown in Table 2.

Table 2. Value of mechanical properties for as received material

As-received material	Experimental Value
Ultimate tensile strength	319.61 MPa
Yield strength	273.85 MPa

3.2 Effect of Cooling Rate

Figure 1 shows the effect of cooling rate after solution treating on ultimate tensile strength (UTS) and yield strength of material. Annealing, normalizing, and quenching represents slow, medium, and the fast cooling rate respectively. The highest ultimate tensile strength of 363.84 MPa was recorded by quenching samples while the lowest was recorded by annealing samples. This finding shows that the strength of heat treated samples does depend on the cooling rate. Faster cooling rate shows higher strength compared to the slow rate. This finding is consistent with Maisonnette et al., (2010), Kelley et al., (2012) and Ridhwan et al., (2013). Lower strength of annealed samples can be attributed to coarse grain that form after recrystallization and relieved of internal lattice strain during annealing (Campbell, 2008). The higher lattice strain could improve the strength of the material via obstruction of dislocation motion which resists deformation, thus, relieved of the internal lattice train will reduce this effect (Callister & Rethwisch, 2011).

The higher strength of quenched samples can be attributed to lattice distortion during water quench which trap precipitating element in solid solution after solution treating. The presence of a precipitating element in solid solution causes a great deal of strain due to mismatch in size between solvent and solute atoms. Consequently, their presence provides higher strength by obstructing and retarding the movement of dislocations (Rafael, 1991).

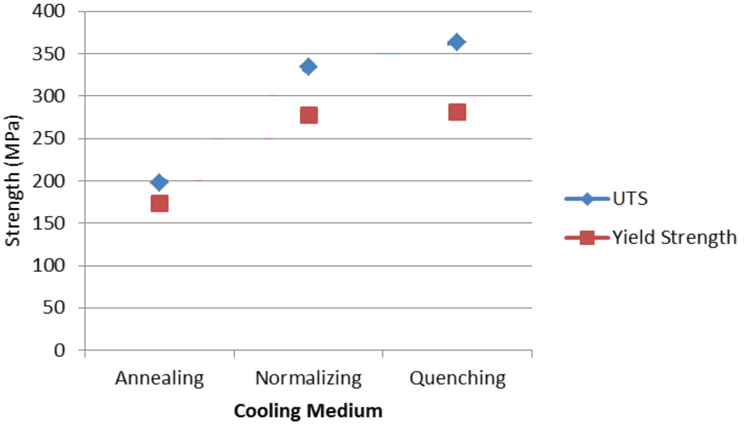

Figure 1. Effect of cooling rate on tensile strength of 6061 aluminum alloy

3.3 Precipitation Hardening

Figure 2 shows the tensile strength of material aged at 100°C from 0.5 to 7 hours. It was observed that the strength of the material increased when the aging time increased. Highest UTS of 625 MPa were recorded at seven hours of aging while the lowest was recorded by 0.5 hour of aging. As there is no drop in strength, it can be concluded that over aging does not take place at this temperature and time interval.

Figure 3 shows the tensile strength of material aged at 200°C. Highest UTS of 567 MPa were recorded in two hours of aging while the lowest by 0.5 hours. The data trend shows that the strength increased when the aging time increased. However, the strength starts to drop after two hours of aging time. This is because, if the part is heated for too long the precipitates grow too large and the primary failure mechanism changes, which reduces the strength of the material (Michael et al., 2010). This phenomenon is known as over aged. This finding is similar as being found by Tan and Muhammad (2009).

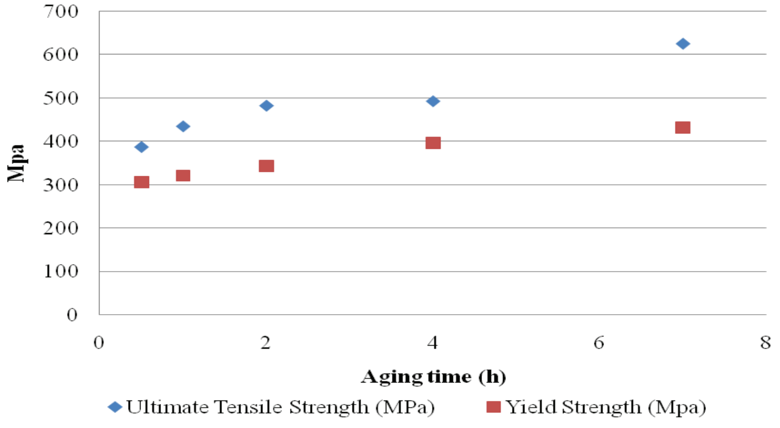

Figure 2. Tensile strength of material undergone precipitation hardening at 100°C

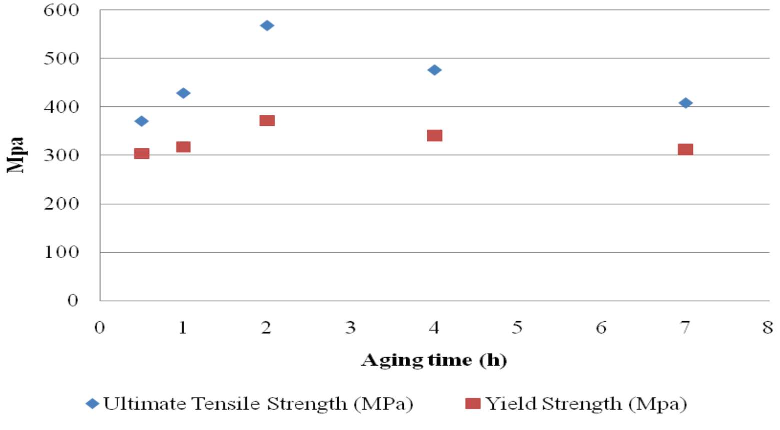

Figure 3. Tensile strength of material undergone precipitation hardening at 200°C

In general, the strength of aging samples was increased substantially as compared to as-received material where the UTS was increased by 95.9% as compared to the as-received. This is because, during aging, precipitating element that trapped during quenching will begin to nucleate, this helps make the material stronger because they act as barriers to dislocation motion (Ridhwan et al., 2013). However, as the aging continues, this precipitates will grow in size and become less effective in strengthening due to poor uniformity along the matrix. This explains the dropped in strength during the over aging period. In addition, the increase in grain size also contributes to the drop in strength during over aged. This is known as Hall-Petch effects where finer grain which consists of the larger grain boundary area will act as an obstruction to dislocation motion, hence, increases the strength of the material. Thus, grain coarsening during over aging will reduce this effect and then decrease the strength of the material. Furthermore, the comparison between these two aging temperature (100^{o}C and 200^{o}C) shows that no peak aged was observed at 100^{o}C while peak aged can be achieved at a shorter aging time when higher temperature was given. This is because aging process performed at lower temperature causes diffusion to reduce and peak aging condition can only be reached in longer times (Rezaei et al., 2010).

3.4 Microstructure Investigation

3.4.1 As-received, annealing, normalizing and quenching

Figure 4 shows the microstructure of as-received, annealed, normalized, and quenched samples. The microstructure of annealed sample shows that the grain size becomes coarser compared to as received. On the other hand, normalized and quenched specimens show finer grain. This is consistent with finding by Rezaei et al., (2010) and Kelley et al., (2012). In general, fast and medium cooling rate results in finer grain whereas slow cooling results to coarse grain. This finding is similar as being found by Ridhwan et al., (2013).

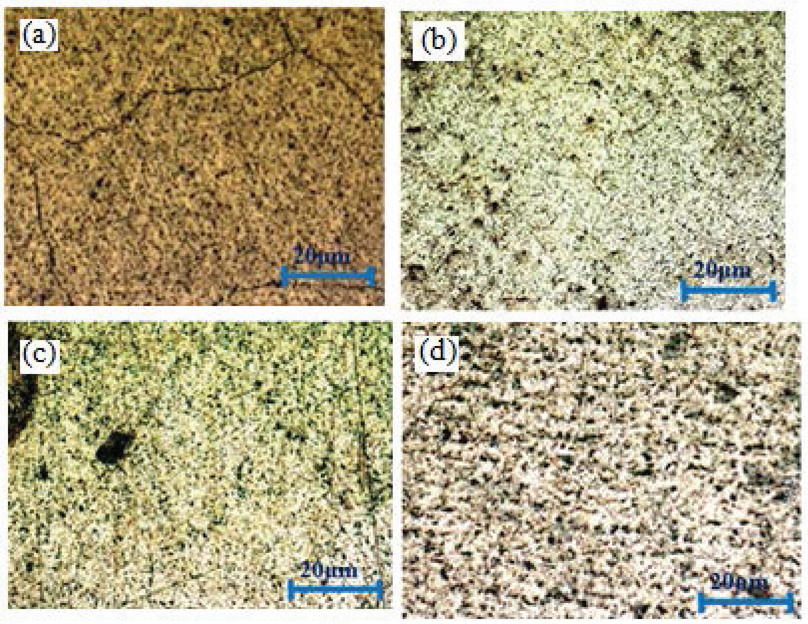

Figure 4. Microstructure with different process
(a) as-received, (b) annealing, (c) normalizing, and (d) quenching

3.4.2 Precipitation Hardening

Figures 5 and 6 show the microstructure of sample undergone precipitation hardening at 100°C and 200°C respectively. It was observed that precipitates were formed on all samples and the precipitates become coarser with longer aging time. As aging temperature increased from 100°C to 200°C, it was observed that the grain and precipitate size become larger. Larger precipitates contribute to the stronger material due to dislocation motion obstruction. However, when the precipitates become too large, it will cause over age as mention previously. In this this study, over-aging was occurred at 200⁰C after two hours of aging which shows larger precipitates size as compare to shorter aging time. Meanwhile, no over aging condition observed at 100°C. Tan and Muhammad (2009) states that finely dispersed of tiny precipitates may contribute to higher hardness and strength, thus, larger precipitates on over-aged samples had lower the strength of material.

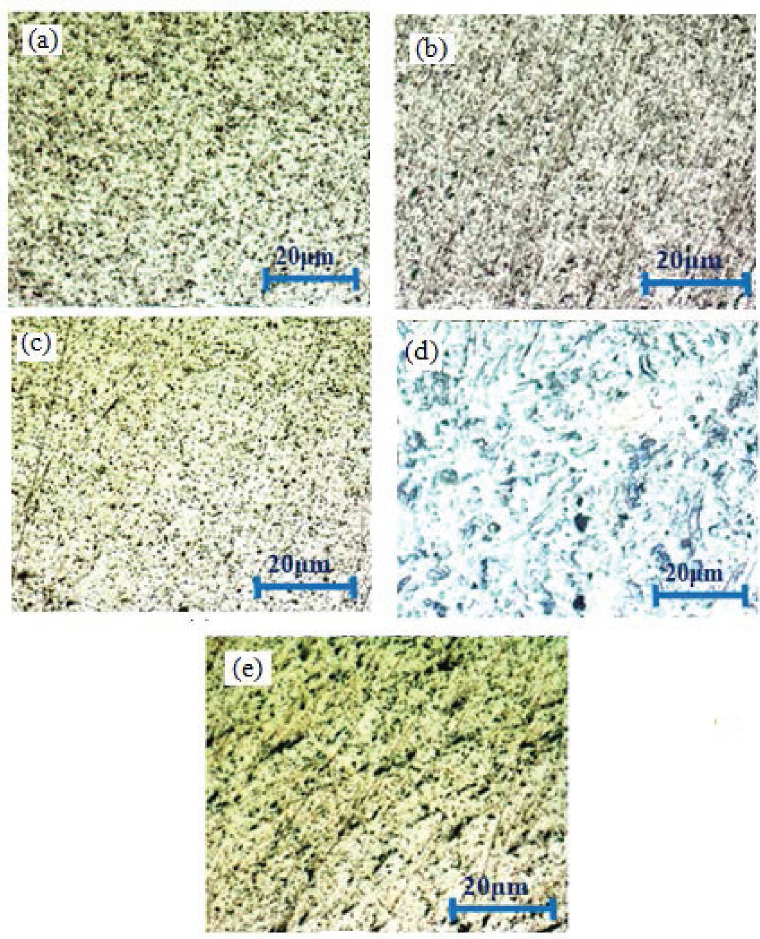

Figure 6. Microstructure for precipitating hardening at $200^{0}C$ for various aging time
(a) 30 minutes; (b) 1 hour; (c) 2 hours; (d) 4 hours; (e) 7 hours

4.0 CONCLUSION

Analysis of the microstructure and strength of heat treated 6061 aluminum alloy has led to a few conclusions:

i. Precipitation hardening at $100^{o}C$ for 7 hours had successfully increased the UTS by 95.9% to 625 MPa due to formation of finely dispersed precipitates. Meanwhile, annealing had lowered the UTS by 62% to 197 MPa due to formation of coarser grain.

ii. Higher cooling rate by quenching and normalizing had increased the strength of the material by formation of finer grain and precipitates as compared to slow cooling by annealing.

iii. Longer precipitation hardening time results to the larger precipitates size which leads to drop in strength (over aged). Meanwhile, higher temperature results in shorter time to reach over age as compared to lower temperature.

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