INFLUENCE OF HEAT TREATMENT ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF 6061 ALUMINUM ALLOY

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ABSTRACT

The process of heat treatment is the method by which metals are heated and cooled in a series of specific operations that never allow the metal to reach the molten state. The purpose of the heat treatment is to cause desire changes in the metallurgical structure and thus in the properties of metal parts. The aim of this research is to study the influence of heat treatment and natural aging mechanism on the microstructure and mechanical properties of aluminum alloy 6061. The aluminum alloy 6061 sample heat treated using T4 method which is heat treated at 550°C, 575°C and 600°C and then naturally aged at ambient environment for 3 hours. After heat treated process, the effects were investigated in terms of microstructure using metallurgical analysis and mechanical properties by tensile tests and hardness test. Tensile tests show that the yield stress and UTS have high value when heat treated at 600°C where 103.28693 MPa and 195.246895 MPa meanwhile the Young modulus heat treated at 550°C have high value; 84417.95106 MPa. For heat treatment specimens, the high VHN is specimen's heat treated at 600°C which have value 85.7 and the lower VHN value is specimen's heat treated at 550°C with value 57.5. The heat treatment process result soft aluminum alloy 6061. Lastly for microstructure observation, different microstructure appear within different heat treatment temperature. From the data and result that already determined, it achieved the objectives and scope of this research.

ABSTRAK

Proses rawatan haba adalah kaedah dimana logam dipanaskan dan disejukkan dalam beberapa siri operasi tertentu yang tidak membenarkan logam untuk mencapai keadaan lebur. Tujuan rawatan haba adalah untuk menyebabkan keinginan perubahan dalam struktur logam dan dengan itu dalam sifat-sifat bahagian logam. Tujuan kajian ini adalah untuk mengkaji pengaruh rawatan haba dan mekanisme penuaan semula jadi pada mikrostruktur dan sifat mekanikal aluminium aloi 6061. Sampel aluminium aloi 6061 dirawat haba menggunakan kaedah T4 yang dirawat haba pada suhu 550°C, 575°C dan 600°C dan kemudian penuaan secara semula jadi di persekitaran ambien untuk 3 jam. Selepas proses dirawat haba, kesan dari segi mikrostruktur telah disiasat menggunakan analisis logam dan sifat-sifat mekanikal dengan ujian tegangan dan ujian kekerasan. Ujian tegangan menunjukkan bahawa tegasan alah dan UTS mempunyai nilai yang tinggi apabila dirawat haba pada 600°C iaitu 103.28693 MPa dan 195.246895 MPa. Sementara itu modulus Young dirawat haba pada 550°C mempunyai nilai yang tinggi; 84417.95106 MPa. Bagi spesimen rawatan haba, VHN yang tinggi adalah spesimen dirawat haba pada 600°C yang mempunyai nilai 85.7 dan nilai VHN lebih rendah adalah spesimen dirawat haba pada 550°C dengan nilai 57.5. Proses rawatan haba menghasilkan aluminium aloi 6061 yang lembut. Akhir sekali untuk pemerhatian mikrostruktur, mikrostruktur yang berbeza muncul dalam suhu rawatan haba yang berbeza. Dari data dan keputusan yang telah ditentukan, ia mencapai objektif dan skop kajian ini.

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LIST OF ABBREVIATIONS

AA	Aluminum alloy
AMS	Aerospace Material Specification
ASM	American Society for Metals
ASTM	American Society for Testing and Materials
FKP	Fakulti Kejuruteraan Pembuatan
FYP	Final Year Project
Max	Maximum
Min	Minimum
OM	Optical Microscope
PCT	Process Critical Temperature
RT	Room Temperature
SCC	Stress Corrosion Cracking
SEM	Scanning Electron Microscopy
SHT	Solution Heat Treatment
TEM	Transmission Electron Microscopy
TS	Tensile Strength
UTS	Ultimate Tensile Strength
VHN	Vickers Hardness Number
Wt	Weight

LIST OF SYMBOLS

%	Percentage
°C	Degree Celsius
°F	Degree Fahrenheit
Al	Aluminum
Cr	Chromium
Cu	Copper
E	Young Modulus
εus	Uniform strain
Fe	Iron
Ftu	Ultimate Strength
Fty	Yield Strength
gf	Gram-force
h	Hour
in	Inches
kg	Kilogram
kgf/mm^2	Kilogram-force per millimeter square
kN	Kilonewton
ksi	Kilopound
Mg	Magnesium
ml	Milliliter
mm	Millimeter
Mn	Manganese
MPa	Megapascal

Si	Silicon
SiC	Silicon Carbide
T_a	Time Aging
T_d	Time Delay
Ti	Titanium
T_s	Solid Solution Time
X	Magnification Times
Zn	Zinc
μm	Micrometer

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Heat treatment is an operation or combination of operations involving heating at a specific rate, soaking at a temperature for a period of time and cooling at some specified rate. The aim is to obtain a desired microstructure to achieve certain predetermined properties (physical, mechanical, magnetic or electrical). This main objective of this thesis is to study the influence of heat treatment on the microstructure and mechanical properties of aluminum alloys.

The process of heat treating is the method by which metals are heated and cooled in a series of specific operations that never allow the metal to reach the molten state. The purpose of heat treating is to make a metal more useful by changing or restoring its mechanical properties. Heat treating can make a metal harder, stronger, and more resistant to impact. Also, heat treating can make a metal softer and more ductile. The one disadvantage is that no heat-treating procedure can produce all of these characteristics in one operation. Some properties are improved at the expense of others; for example, hardening a metal may make it brittle.

Aluminum (nonferrous metal) is a white, lustrous metal, light in weight and corrosion resistant in its pure state. It is ductile, malleable, and nonmagnetic. Aluminum combined with various percentages of other metals, generally copper, manganese, and magnesium, form the aluminum alloys that are used in aircraft construction. Aluminum alloys are lightweight and strong but do not possess the corrosion resistance of pure aluminum and are generally treated to prevent deterioration. "Alclad" is an aluminum alloy with a protective coating of aluminum to make it almost equal to the pure metal in corrosion resistance.

Several of the aluminum alloys respond readily to heat treatment. In general, this treatment consists of heating the alloy to a known temperature, holding this temperature for a definite time, then quenching the part to room temperature or below. During the heating process, a greater number of the constituents of the metal are put into solid solution. Rapid quenching retains this condition, which results in a considerable improvement in the strength characteristics.

Aluminum alloy’s lightweight performance delivers great benefit in transport applications such as aerospace, cars, ships, trains and buses. The metal’s excellent characteristics help give automotive and other transport users improved driving performance as well as increasing fuel economy and reducing emissions. Another significant advantage of aluminum alloy is its corrosion resistance. This characteristic is valuable for products used in architecture, construction, civil engineering, transport, heat exchangers and many other applications.

1.2 PROJECT OBJECTIVE

This paper is about influence of heat treatment on the microstructure and mechanical properties of aluminum alloys. The objectives of the project are:

(i) To study and analyze the effect of solution heat treatment and natural aging mechanism.

(ii) To investigate the microstructure changes and mechanical properties of aluminum alloys 6061.

1.3 PROBLEM STATEMENT

Aluminum is subject to internal stresses and strains when it is overheated, the tendency of the metal to creep under these stresses tends to result in delayed distortions. For example, the warping or cracking of overheated aluminum automobile cylinder heads is commonly observed. Stresses in overheated aluminum can be relieved by heat treating the parts in an oven and gradually cooling it in effect annealing the stresses. Heat treatment can change the material properties in terms of its strength and resistance properties. The change in microstructure of the material when heat treated can influence the mechanical properties and the microstructure of the aluminum alloy.

1.4 PROJECT SCOPE

The scopes of this project are:

(i) Solution heat-treated and naturally aged; T4 type tempers.
(ii) Study the microstructure of aluminum alloys 6061 using optical microscope.
(iii) Investigation on the mechanical properties using tensile and hardness test.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

A review of the literature review was performed to identify studies relevant to heat treatment process, properties of the material and testing method involved. A review of others relevant research also provided in this chapter. The review is detailed so that the information and older research can be used to improve this topic.

2.2 ALUMINUM ALLOYS

Aluminum alloys is one of the nonferrous metal. Nonferrous metal and alloys cover a wide range, from the more common metals (such as aluminum, copper and magnesium) to high-strength, high-temperature alloys (such as those of tungsten, tantalum and molybdenum). Although generally more expensive than ferrous metal, nonferrous metal and alloys have numerous important applications because of properties such as good corrosion resistance, high thermal and conductivity, low density and ease of fabrication. (Kalpakjian, S. & Schmid S.R, 2010)

Pure aluminum is soft and ductile. Most commercial uses require greater strength than pure aluminum affords. Aluminum is a lightweight structural material that can be strengthened through alloying and depending upon composition, further strengthened by heat treatment and cold working. This is achieved in aluminum by addition of other elements to produce various strength level alloys. Aluminum and its alloys appear to have increasing applications and to be competitive to ferrous alloys due to their important advantages such as, low density, high specific strength, high corrosion resistance, good formability and weldability (Hatch, J.E, 1984).

Table 2.1: Wrought alloy designation system

Number Element	Major Alloying Element
1XXX	Aluminum (99.00% minimum)
2XXX	Copper
3XXX	Manganese
4XXX	Silicon
5XXX	Magnesium
6XXX	Magnesium and Silicon
7XXX	Zinc
8XXX	Other element
9XXX	Unused Series

Source: ASM Handbook

Aluminum alloy are identified by a four-digit number, the first digit of which generally identifies the major alloying element as shown in the Table 2.1. For aluminum alloys, the fourth digit is separated from digit by a decimal point and indicates the form.

2.2.1 The Aluminum Alloys 6061

AA6061 which is in group 6XXX alloys contain Si and Mg as main alloying elements, with other elements, such as Cu and Mn, for improving mechanical properties. The physical process effective in heat treating 6XXX alloys is precipitation hardening and can be divided into three steps: During solution heat treatment (SHT) at a temperature T_s for a period t_s a solid solution of the alloying elements is formed. Quenching at a rate $(dT/dt)_q$ allows for stabilizing this state at room temperature, thus leading to a supersaturated solid solution. After an optional delay time t_d, ageing at temperature T_a for a period t_a leads to the formation of precipitates in fine dispersion within the supersaturated regions (Lehmus D., & Banhart J., 2002).

Aluminum-magnesium-silicon alloys (6XXX) are medium strength, heat treatable alloys that generally possess excellent SCC resistance. They are strengthened primarily by the aging precipitate Mg_2Si. The most commonly used alloy, 6061, contains a stoichiometric balance of magnesium and silicon to form Mg_2Si. Excess silicon is added to other alloys for increase strength but the excess silicon alloys can be rendered more susceptible to SCC by improper heat treatments (Hatch, J. E., 1984). AA6061 was also intended to serve as a prototype for age-hardenable alloys. Results of a general nature are expected which would be transferable to other alloys (Lehmus D., & Banhart J., 2002).

2.2.2 Chemical Composition and Mechanical Properties of Aluminum Alloy 6061

Typical chemical composition and mechanical properties for aluminum alloy 6061 was state in Table 2.2 and Table 2.3.

Table 2.2: Typical chemical composition of aluminum alloy 6061

Element	**Al**	**Mg**	**Si**	**Fe**	**Cu**	**Zn**	**Ti**	**Mn**	**Cr**	**Other**
Amount (Wt %)	Balance	0.8-1.2	0.4-0.8	Max .0.7	0.15-0.40	Max. 0.25	Max. 0.15	Max. 0.15	0.04-0.35	0.05

Table 2.3: Typical mechanical properties of aluminum alloy 6061

Temper	**Ultimate Tensile Strength (MPa)**	**0.2% Proof Stress (MPa)**	**Brinell Hardness (500kg load, 10mm ball)**	**Elongation 50mm dia. (%)**
0	110-152	65-110	30-33	14-16
T1	180	95-96		16
T4	179 min	110 min		
T6	260-310	240-276	95-97	9-13

2.2.3 Microstructure of Aluminum Alloy 6061

More highly alloyed 6061 generally have an excess of Mg_2Si at the solutionizing temperature and if slowly cooled, precipitates in a Widmrenstatten form, show in Figure 2.1 (Hatch, J. E., 1984).

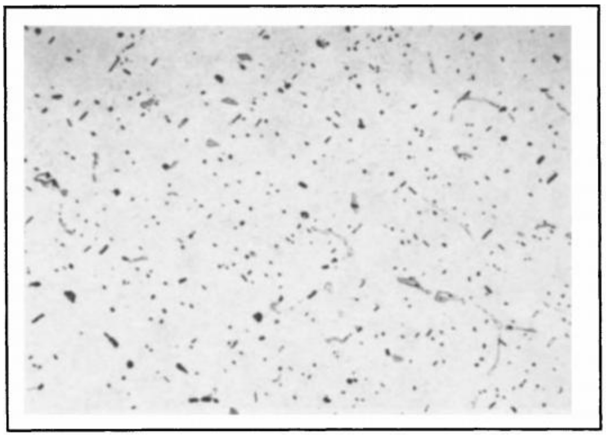

Figure 2.1: 6061 homogenized ingot showing some undissolved Mg_2Si and some Mg_2Si reprecipitation during cooling in a Widmrenstatten pattern. 0.5% hydro-fluoric acid, 455 x.

Source: Courtesy of Kaiser Aluminum & Chemical Corp.

Solution heat treated 6061 appears as shown in Figure 2.2, where T4 and T6 tempers cannot be readily distinguished. Special etching techniques can be used to make a distinction; in Figure 2.3, but it is best to have a known standard to use for comparison (Hatch, J. E., 1984).

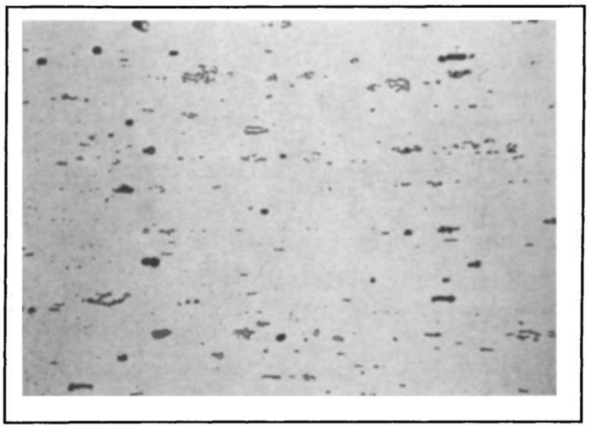

Figure 2.2: 6061-T6 sheet showing insoluble (Fe, Cr)$_3$ SiAl$_{12}$ and excess soluble Mg_2Si particles (dark) as redistributed by mechanical working. 0.5% hydrofluoric acid, 455 x.

Source: Courtesy of Kaiser Aluminum & Chemical Corp.

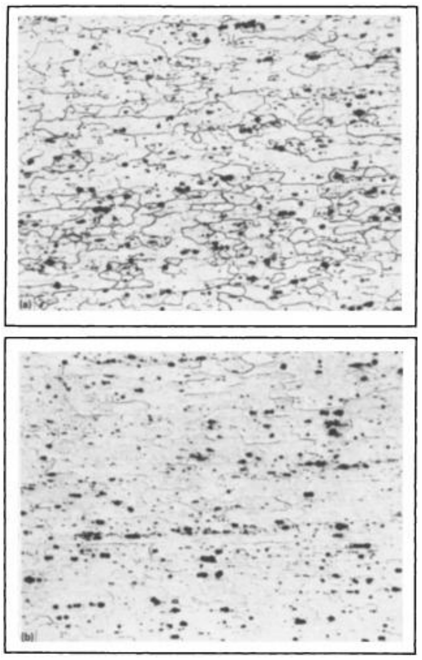

Figure 2.3: 6061-T4 (a) and T6 (b) sheet showing the typical constituent distribution and loss of clear grain delineation caused by Mg_2Si precipitation from artificial aging. Hydrofluoric acid and sulfuric acid, 230X.

Source: Courtesy of Kaiser Aluminum & Chemical Corp.

2.3 PURPOSE OF HEAT TREATMENT

The process of heat treating is the method by which metals are heated and cooled in a series of specific operations that never allow the metal to reach the molten state. The purpose of heat treating is to make a metal more useful by changing or restoring its mechanical properties. Through heat treating, we can make a metal harder, stronger, and more resistant to impact. Also, heat treating can make a metal softer and more ductile.

The purpose of the heat treatment is to cause desire changes in the metallurgical structure and thus in the properties of metal parts. Differences in type, volume fraction, size, and distribution of the precipitated particles govern properties as well as the changes observed with time and temperature and these are all affected by the initial state of the structure. The initial structure may vary in wrought products from unrecrystallized to recrystallized and may exhibit only modest strain from quenching or additional strain from cold working after solution heat treatment. These conditions, as well as the time and temperature of precipitation heat treatment, affect the final structure and the resulting mechanical properties (Totten, G.E., 1997).

2.3.1 Heat Treatment on Aluminum Alloys

Heat treating is a critical step in the aluminum manufacturing process to achieve required end-use properties. The heat treatment of aluminum alloys requires precise control of the time-temperature profile, tight temperature uniformity and compliance with industry-wide specifications so as to achieve repeatable results and produce a high-quality, functional product. The most widely used specifications are AMS2770 (Heat Treatment of Wrought Aluminum Alloy Parts) and AMS2771 (Heat Treatment of Aluminum Alloy Castings) (ASM Handbook), which detail heat-treatment processes such as aging, annealing and solution heat treating in addition to parameters such as times, temperatures and quenching. These specifications also provide information on necessary documentation for lot traceability and the quality-assurance provisions needed to ensure that a dependable product is produced.

Wrought aluminum alloys can be divided into two categories: non-heat treatable and heat treatable. Non-heat-treatable alloys, which include the 1xxx, 3xxx, 4xxx and 5xxx series alloys derive their strength from solid solution and are further strengthened by strain hardening or, in limited cases, aging. Heat-treatable alloys include the 2xxx, 6xxx and 7xxx series alloys and are strengthened by solution heat treatment followed by precipitation hardening (aging) (Mwahid A.L. and Jaafar S).

The heat treatment consists of one or more thermal cycles being applied to the aluminum alloy components. Generally, the thermal treatments are designed by suffixes and main ones are as follows:

- M - As cast or as manufactured
- TB or T4 - Solution treated and naturally aged
- TE or T5 - Artificially aged
- TB7 - Solution treated and stabilized
- TF of T6 - Solution heat treated and fully artificially aged
- TF7 - Solution treated and artificially aged and stabilized
- TS - Stress relieved and annealed

2.3.2 Heat Treatment of Aluminum Alloy 6061

Most heat treatments aim at controlling strength and ductility. For AlMgSi and related alloys, maximum strength is achieved by means of precipitation hardening at the cost of ductility. Ductility can be increased via annealing - at the cost of strength. In order to cover the entire range of heat treatments, the investigations included complete precipitation hardening cycles as well as pure annealing treatments (Lehmus D., & Banhart J., 2002).

In the annealed condition (-O temper), 6061 is extremely ductile and well suited for severe forming applications. When solution heat-treated and naturally aged (-T4 condition), 6061 has good formability for bending. After artificial aging (precipitation heat-treating), 6061-T4 is capable of developing -T6 properties. (Alcoa Engineered Products, 2002)

Table 2.4: 6061 temper designations and definitions

Standard Tempers	**Standard Temper Definitions**
F	As fabricated. There is no special control over thermal conditions and there are no mechanical property limits.
O	Annealed. Applies to products that are annealed to obtain the lowest strength temper.
T1	Cooled from an elevated temperature shaping process and naturally aged.
T4, T4511	Solution heat-treated and naturally aged.
T51	Cooled from an elevated temperature shaping process and artificially aged.
T6, T6511	Solution heat-treated and artificially aged.

Source: Alcoa Engineered Products, 2002

In this study, the aluminum alloy 6061 sample will be heat treated using methods T4 heat treatment. 6061-T4 condition is achieved by solution heat treating the material followed by natural aging. Natural aging is the process that allows the material to precipitation harden at room temperature. Solution heat treated and naturally aged to a substantially stable condition T4 is applies to products that are not cold worked after solution heat treatment or in which effect of cold work is flattening or straightening may not be recognized in mechanical property limits (Hatch, J. E., 1984).

2.3.2.1 Solution Treatment

The purpose of solution heat treatment is the dissolution of the maximum amount of soluble elements from the alloy into solid solution. The solution treatment consists of heating the alloy to the temperature at which the principal constituents go into solid solution, soaking the alloy at this temperature to produce a uniform structure,