# HEAT TREATMENT PROCESS OF ALUMINIUM ALLOY TO MINIMIZE THE PRECIPITATE FREE ZONES AND IT EFFECT TO WEAR RESISTANCE

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## ABSTRACT

Heat treating processes for aluminum are precision processes. Based on the objectives of this research, Precipitate Free zones in the aluminum alloy 6061 actually give bad effect to the mechanical properties of that alloy. The mechanical properties of the aluminum alloy should be altering properly to improve their behavior using precipitation hardening which one of the heat treatment types. Precipitation hardening is the most suitable heat treatment that should use to minimize the precipitate free zones in the microstructure of the aluminum alloy 6061 series. In the precipitation hardening process, the thermal and temperature condition is under control with high precision to ensure the transformation of the aluminum alloy structure is in good condition and supervision limit. The samples of the material are placed in the furnace to make a heating process and then quench it in the water for quenching medium. The material testing that had been applied is based on hardness, impact and microstructure analysis. The purpose of the hardness testing are to find out the hardness reading for all samples that used to look the wear resistance effect that occur after make a heat treating process to the aluminum alloy 6061. From the impact test, the purposes are to know impact energy that absorbed to fracture the samples of the material and then make a comparison data between after and before heat treat treatment. Lastly, for microstructure analysis it is important to determine because to look the narrow evaluation of precipitate free zones in the microstructure of aluminum alloy after make a precipitation hardening process. From the data and result that already determined, it shown the positive result based on the objectives and scope of this project.

# ABSTRAK

Proses rawatan haba adalah proses yang memerlukan ketelitian dan kawalan yang meyeluruh. Berdasarkan kepada objektif kajian ini pemendakan kawasan bebas dalam aloi aluminium siri 6061 sebenarnya mendatangkan kesan buruk kepada sifat-sifat mekanikal aloi tersebut. Bagi meningkatkan keupayaan sifat-sifat mekanikal aloi tersebut seperti kekerasan dan kemuluran rawatan haba perlu dilakukan dengan menggunakan kaedah pemendakan pengerasan dimana ia adalah jenis rawatan haba yang sesuai diaplikasi bagi mengurangkan luas pemendakan kawasan bebas. Dalam teknik pemendakan pengerasan, haba dan suhu ditetap dan diselaraskan mengikut piawaian aloi aluminium yang digunakan serta pengawasan yang teliti. Sampel aloi yang digunakan akan dibakar didalam ketuhar pembakaran pada suhu tinggi bagi mengubah struktur aloi aluminium tersebut daripada keadaan asal. Kemudian sampel tersebut akan melalui proses penyejukan dengan menggunakan air sebagai medium penyejukan bagi kajian ini. Terdapat tiga keadaan yang diaplikasikan iaitu pemeraman penyejukan sampel, pemeraman semulajadi sampel dan pemeraman pemanasan sampel dimana perbandingan keputusan diantara ketiga-tiga keadaan tersebut. Ujian bahan yang digunakan dalam kajian ini ialah ujian kekerasan, ujian pelanggaran dan analisis terhadap mikrostruktur sampel tersebut. Bagi ujian kekerasan ia penting bagi melihat perubahan sifat kehausan bahan tersebut selepas menjalani proses rawatan haba dan ujian keliatan pula adalah untuk melihat tahap keliatan sampel aloi selepas proses rawatan haba berdasarkan jumlah tenaga pelanggaran yang diserap bagi mematahkan sampel aloi aluminium siri 6061 dan membuat perbandingan data sebelum melakukan rawatan haba. Selain itu, analisis terhadap mikrostruktur aloi dilakukan adalah untuk melihat perubahan kawasan pemendakan bebas samada ia semakin sempit atau tidak serta membuat perbandingan di antara tiga keadaan iaitu pemeraman penyejukan sampel, pemeraman semulajadi sampel dan pemeraman pemanasan sampel.

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

Aluminum is for structural application, therefore it is usually alloyed with several elements to improve its corrosion resistance, inhibit grain growth and to increase its strength. Aluminum naturally generates a protective oxide coating and is highly corrosion resistant. Different type of surface treatment such as anodizing, painting or lacquering can further improve this property. It is particularly useful for applications where protection and conservation are required. The optimum strengthening of aluminum is achieved by alloying and heat treatments. There are many type of aluminums alloy series in it alloy systems which the each series has their own mechanical and physical properties depends on the composition in that alloys (P.J. Gregson and S.J. Harris, 2002).

The main components of the 6000 series alloys are magnesium and silicon to form **$Mg_2Si$**. There is often an iron corrector such as manganese or chromium; occasionally small amounts of copper or zinc to improve the strength without substantial loss of corrosion resistance; boron in conductors to remove titanium and vanadium; zirconium or titanium to control the grain size. Lead and bismuth are sometimes added to improve machinability, but they are less effective than in magnesium-free alloys.

That promotes the formation of small, hard precipitates, which interfere with the motion of dislocations. The strengthening properties of aluminum are achieved by making an alloying process with other material with a good combination of composition in the aluminum alloy. The strength of aluminum also can be defined with heat treatment process which that promote the formation of small, hard precipitates which interfere with the motion of dislocations. Aluminum alloys that can be heat treated to form these precipitates are considered heat treatable alloys. Pure aluminum is not heat treatable because no such particles can form while many heat treatable aluminum alloys are not weldable because welding would destroy the microstructure produced by careful heat treatment.

Normally, heat treatment aluminum alloy would be strengthened with precipitation hardening process of that alloy. Precipitation hardening (otherwise known as age hardening) is a process whereby a fine precipitate structure is formed in the alloy matrix following a heat treatment process. Precipitation hardening is involves raising the temperature of the alloy into single phase region so that all of the precipitates dissolve. These alloys actually are quenched to form the supersaturated solid solution in the phase diagram of this alloy. It is can also excess the vacancy and dislocation loop, which can be act as nucleation for precipitation hardening.

This process can come slowly at the room temperature and quickly move at evaluated temperature typically 100°C to 200°C (artificial aging). The degree of precipitation hardening are obtained depends on the size, number and relative strength of the precipitates. These factors are determined by the composition of the alloy and by the tempering temperature and tempering time. The distribution of precipitates affects the hardness and yield strength. The hardness and yield strength are greater when the precipitates are small and finely dispersed in the kappa matrix than when the precipitates are large and not finely scattered.

## 1.2 Project Background

The types of 6XXX alloy are among those, which have responded positively to modify ageing procedure involving, interrupted ageing. These alloy widely used of medium strength with major application as extrusion product and automotive body sheet. These alloys undergo a complex decomposition during ageing and despite their commercial importance, the understanding of the precipitation process in these alloys still incomplete. Mechanical properties of the commercial alloys depend on content of **Mg, Si, Cu** and other alloying elements, treatment conditions (cold or hot treatment) and heat treatment. Commercial alloys, especially if they contain manganese or chromium, may show strengths some 10% higher. High strain rates lead to somewhat better properties. Fully hardened alloys show some tendency to intergranular fractures in tension testing, but manganese additions reduce this tendency. Silicon precipitates, as platelets, may be responsible for this brittleness.

Compressive strength is practically the same as tensile even at elevated temperatures. Shear strength is of the order of 70% of the tensile and is not substantially affected by subzero temperatures or nuclear radiation. The modulus of elasticity is of the order of 65 GPa. Heat treatment of the alloys is not too critical; in many alloys the temperature at which all the soluble constituents are dissolved is well below that of the beginning of melting. Heat treatment temperatures range from 720 to 850K. Solution treatment of wrought products requires very short times, reportedly of the order of seconds. High-temperature deterioration may result in dimensional growth.

## 1.3 Objective

For this project of research about heat treatment processes of aluminum alloy to minimize the precipitate free zones and it effect to the wear resistance of material, the main aim of the present work were to identify or determine the most suitable heat treatment process for aluminum alloys composition to eliminate and reduce the precipitate free zones and to look and study about wear resistance for aluminum alloy series and with heat treatment process.

## 1.4 Scope

The scopes of this research are based on the precipitation hardening processes of aluminium alloy 6061 series and also to look the effecting of heating process to the mechanical properties especially wear resistance of the material.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

This chapter is intended to provide a lot of information about extensive background of heat treatment process with detail explanations as a reference for this research. The chapter begins with general overview of type of heat treatment process and also the mechanism of the precipitation hardening process.

## 2.2 Heat Treatment Process

The term “heat treating” for aluminum alloys is frequently restricted to the specific operations employed to increase strength and hardness of the precipitation-hardenable wrought and cast alloys. These usually are referred to as the “heat-treatable” alloys to distinguish them from those alloys in which no significant strengthening can be achieved by heating and cooling (Article www.key-to-metal.com). Heat treating in its broadest sense, refers to any of the heating and cooling operations are performed for the purpose of changing the mechanical properties, the metallurgical structure, or the residual stress state of a metal product (M Kellent, 2003).

## 2.3 Types of Heat Treatment

Heat treatments applied to aluminum and its alloys are **Preheating** or homogenizing to reduce chemical segregation of cast structures and to improve material workability. **Annealing** to soften strain-hardened (work-hardened) and heat-treated alloy components, to relieve stresses and to stabilize properties and dimensions. **Precipitation (age-hardening)** heat treatment to provide hardening by precipitation of constituents from solid solution. **Solution heat treatment** to improve mechanical properties by putting alloying elements into solution.

## 2.4 Heat Treatable Aluminum Alloys

The precipitation hardening process follows three main steps. **Solution treatment**, which the alloy is heated above the solvus temperature to dissolve any precipitates and ensure the alloying elements, is in solid solution. Besides that, **quench** which the alloy is quenched. The alloying elements in solution do not have time to diffuse and form precipitates. Thus, the alloying elements remain in solution forming what is known as a supersaturated solid solution. **Aging** which that alloys is heated to an intermediate temperature below the solvus temperature. The alloying elements are able to diffuse to form coherent precipitate clusters (known as GP zones).

The coherent precipitates increase the strength of the alloy by distorting the crystal lattice and creating resistance to dislocation motion. The number of precipitates increases with increasing time thus increasing the strength of the alloy. However, with excessive time the precipitates become large and incoherent and their strengthening effect decreases (R.G O'Donell, 2004). Thus, during precipitation hardening there are four main stages which solid solution strengthening in the supersaturated solid solution, coherency stress hardening from the coherent precipitates, precipitation hardening by resistance to dislocation cutting, hardening through resistance to dislocation between precipitates.

### 2.4.1 Solution Heat Treating

To take advantage of the precipitation hardening reaction, it is necessary first to produce a solid solution. The process by which this is accomplished is called solution heat treating, and its objective is to take into solid solution the maximum practical amounts of the soluble hardening elements in the alloy. The processes consist of soaking the alloy at a temperature sufficiently high and for a time long enough to achieve a nearly homogeneous solid solution (J. W Martin Precipitation Hardening, 1998).

### 2.4.2 Precipitation Heat Treating without Prior Solution Heat Treatment

Certain alloys that are relatively insensitive to cooling rate during quenching can be either air cooled or water quenched directly from a final hot working operation. In either condition, these alloys respond strongly to precipitation heat treatment. This practice is widely used in producing thin extruded shapes of alloys 6061, 6063, 6463 and 7005. Upon precipitation heat treating after quenching at the extrusion press, these alloys develop strengths nearly equal to those obtained by adding a separate solution heat treating operation. Changes in properties occur during the precipitation treatment follow the principles outlined in the discussion of solution heat-treated alloys.

### 2.4.3 Quenching

Quenching is in many ways the most critical step in the sequence of heat-treating operations. The objective of quenching is to preserve the solid solution formed at the solution heat-treating temperature, by rapidly cooling to some lower temperature, usually near room temperature. In most instances, to avoid those types of precipitation that are detrimental to mechanical properties or to corrosion resistance, the solid solution formed during solution heat treatment must be quenched rapidly enough (and without interruption) to produce supersaturated solution at room temperature - the optimum condition for precipitation hardening (Douglas Breton, 2000). The resistance to stress-corrosion cracking of certain copper-free aluminum-zinc-magnesium alloys, however, is improved by slow quenching. Most frequently, parts are quenched by immersion in cold water, or in continuous heat treating of sheet, plate, or extrusions in primary fabricating mills, by progressive flooding or high-velocity spraying with cold water.

### 2.4.4 Age hardening

After solution treatment and quenching hardening is achieved either at room temperature (natural aging) or with a precipitation heat treatment (artificial aging). In some alloys, sufficient precipitation occurs in a few days at room temperature to yield stable products with properties that are adequate for many applications. These alloys sometimes are precipitation heat treated to provide increased strength and hardness in wrought or cast products. Other alloys with slow precipitations reactions at room temperature are always precipitation heat treated before being used. In some alloys, notably those of the 6xxx series, cold working or freshly quenched material greatly increases its response to later precipitation heat treatment (Serdar Z. Elgun, 1999).

**Natural Aging.** The more highly alloyed members of the 6xxx wrought series, the copper-containing alloys of the 7xxx group, and all of the 2xxx alloys are almost always solution heat treated and quenched. For some of these alloys, particularly the 2xxx alloys, the precipitation hardening that results from natural aging alone produces useful tempers (T3 and T4 types) that are characterized by high ratios of tensile to yield strength and high fracture toughness and resistance to fatigue (Smith W, 1999). For the alloys that are used in these tempers, the relatively high supersaturation of atoms and vacancies retained by rapid quenching causes rapid formation of GP zones, and strength increases rapidly, attaining nearly maximum stable values in four or five days. Tensile-property specifications for products in T3-

and T4-type tempers are based on a nominal natural aging time of four days. In alloys for which T3- or T4-type tempers are standard, the changes that occur in further natural aging are of relatively minor magnitude, and products of these combinations of alloy and temper are regarded as essentially stable after about one week. In contrast to the relatively stable condition reached in a few days by 2xxx alloys that are used in T3- or T4-type tempers, the 6xxx alloys and to an even greater degree the 7xxx alloys are considerably less stable at room temperature and continue to exhibit significant changes in mechanical properties for many years.

**Precipitation heat treatments** generally are low-temperature, long-term processes. Temperatures range from 115 to 190°C; times vary from 5 to 48 h. Choice of time-temperature cycles for precipitation heat treatment should receive careful consideration. Larger particles of precipitate result from longer times and higher temperatures; however, the larger particles must, of necessity, be fewer in number with greater distances between them. The objective is to select the cycle that produces optimum precipitate size and distribution pattern. Unfortunately, the cycle required to maximize one property, such as tensile strength, is usually different from that required to maximize others, such as yield strength and corrosion resistance. Consequently, the cycles used represent compromises that provide the best combinations of properties. Production of material in T5- through T7-type tempers necessitates precipitation heat treating at elevated temperatures (artificial aging) (ASTM of Aluminium Alloy, 1999).

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 recrystallize 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. Precipitation heat treatment following solution heat treatment and quenching produces T6- and T7-type tempers. Alloys in T6-type tempers generally have the highest strengths practical without sacrifice of the minimum levels of other properties and characteristics found by experience to be satisfactory and useful for engineering applications. Alloys in T7 tempers are overaged, which means that some degree of strength has been sacrificed or "traded off" to improve one or more other characteristics.

Strength may be sacrificed to improve dimensional stability, particularly in products intended for service at elevated temperatures, or to lower residual stresses in order to reduce warpage or distortion in machining. T7-type tempers frequently are specified for cast or forged engine parts. Precipitation heat-treating temperatures used to produce these tempers generally are higher than those used to produce T6-type tempers in the same alloys.

Two important groups of T7-type tempers the T73 and T76 types have been developed for the wrought alloys of the 7xxx series, which contain more than about 1.25% copper. These tempers are intended to improve resistance to exfoliation corrosion and stress-corrosion cracking, but as a result of overaging, they also increase fracture toughness and, under some conditions, reduce rates of fatigue-crack propagation.

## 2.5 Precipitation Hardening

This Process actually when the properties of strength and hardness of some alloy may be changed by the formation process of extremely small uniformly dispersed particles of a second phase within the original matrix. This phase of heat treatment consists of aging material previously subjected to solution heat treatments by natural (occurs at room temperature) or artificial aging. Artificial aging consists of heating aluminum alloy to a specific temperature and holding for a specified length of time. During this hardening and strengthening operation the alloying constituents in solid solution precipitate out. As precipitation progresses, the strength of the material increases until the maximum is reached. Further aging (overaging) causes the strength to decline until a stable condition is obtained. The strengthening of material is due to the uniform alignment or formation of the molecule structure of the aluminum and alloying element. The phase transformations are induced by appropriates heat treatment process. This is called Precipitation Hardening because the small particles of a new phase are termed precipitates. Precipitation hardening (otherwise known as age hardening) (C. D. Marioara, S. J. Andersen, 2004). For an alloy to be precipitation hardened it requires to decreased solid solubility with decreasing temperature, the ability to suppress the formation of precipitates by quenching from a solid solution and the formation of metastable coherent precipitates.

## 2.6 Aluminum

Aluminum has the chemical symbol Al, atomic number 13, and atomic weight 26.98. The isotope with mass number 27 is the only stable isotope. Aluminum is a very light metal with a specific weight of 2.7 kg $dm^{-3}$, about a third that of steel. For example, the use of aluminum in vehicles reduces dead-weight and energy consumption while increasing loads capacity. Its strength can be adapted to the application required by modifying the composition of its alloys and by various thermal and mechanical treatments.

It is a soft, light, gray metal that resists corrosion when pure in spite of its chemical activity because of a thin surface layer of oxide. It is nonmagnetic and nonsparking. Its density is 2.6989 $g/cm^3$, melting point 669.7°C and boiling point 1800°C. Its electrical resistivity is 2.824 µΩ-cm at 20°C, with temperature coefficient 0.0039$°C^{-1}$, the same as coppers. Its thermal conductivity is 2.37 W/cm-K at 300K, and the linear coefficient of expansion is 23.86 x $10^{-6}°C^{-1}$. The specific heat is 0.2259 cal/g-K, and the heat of fusion is 93 cal/g. The first ionization potential is 5.96V, second 18.74V and third 28.31V. Its electrode potential is 1.67V positive with respect to hydrogen. When near its melting point, it becomes "hot short" and crumbles easily (ASTM of Aluminum Alloy, 2003).

As a pure metal, it is quite soft, and must be strengthened by alloying with Cu, Mg, Si or Mn before it can be used structurally. Aluminum bronze is 90 Cu, 10 Al, a strong, golden-yellow alloy with excellent physical properties. The Young's modulus of pure aluminum is 68 GPa, the shear modulus 25 GPa, Poisson's ratio 0.33, and the ultimate tensile strength 68.94 MPa, with 60% elongation. Pure aluminum is very ductile and malleable, and unsuitable as a structural material. Its hardness is 15 Brinell (500 kg, 10 mm). The useful wrought alloys contain 1-7% magnesium and 1% manganese. Its crystal form is face-centered cubic, with lattice constant a = 0.404 nm, and nearest-neighbor spacing of 0.286 nm (I. J Polmear, 2000).

## 2.7 Aluminum and its alloy

Aluminum and it alloys are characterized by a relatively low Density (2.7 g/cm3, it have high electrical and thermal conductivities, and a resistance to corrosion in some common environment, including the ambient atmosphere. Some of alloys are easily to be formed by virtue of high ductility, which this is evidenced by the thin aluminum foil sheet into which the relatively pure material may be rolled.

Generally, aluminum alloy are divided into some of categories such as wrought and casting alloy. The composition both of alloy is designated by four digit number that it is indicates the principles impurities and in some chase, the purity level. It's had the properties of mechanical and may be enhanced by cold work and alloying process between other materials. But, both processes are tending to diminish resistance to corrosion. The principles of aluminum alloy elements are including copper, magnesium, silicon, manganese, and also zinc. There are two types of heat treatable alloying which the Non-Heat Treatable and also the other one is heat treatable alloys (capable of being precipitation hardening). The non-heat treatable alloys are consist of a single phases which it is increase in strength and achieved by solid solution strengthening (B. Michael 1998).

Aluminum alloy 6061 is the least expensive and most versatile of the heat-treatable alloys. It is a favorite alloy of many fabricators as it is a weldable alloy with moderate to high strength in tempered condition. It also has good formability in the annealed condition. It is the best choice for intake manifold and inter-cooler plumbing due to the weldability and formability of the alloy (Raphel, 2004). As previously mentioned, heat-treating improves the strength of aluminum alloys through a process known as precipitation hardening. In simple terms, precipitation hardening is a process that occurs during the heating and cooling of an aluminum alloy in which minute particles or precipitates are formed in the aluminum matrix. These particles reduce slippage between grains, which in turns increases material hardness, and strength.

### 2.7.1 Non-Heat treatable Aluminum Alloy

The aluminum 1XXX in this group has 99% purity and it is non heat treatable alloy. The best use for this series is in electrical, chemical, and other applications where good corrosion resistance, high electrical and thermal conductivity, and excellent workability are important. Application in chemical equipment, reflectors, heat exchangers, electrical conductors. Manganese 3XXX is the principle alloy in this series and though there are few alloys in this series, some of these more popular sheet alloys provide good workability and moderate. A common example of a consumer product is soda cans. Magnesium in 5XXX is the major alloy of this group. These alloys are non-heat treatable; provide good weldability, and good marine corrosion resistance. An alloy in this series is commonly used in the production of beverage can lids strength

### 2.7.2 Heat Treatable Aluminum Alloy

The principle alloy of 2XXX series is copper. These alloys require heat treating and their mechanical properties can exceed that of mild steel. The 2000 series does not have good corrosion resistance but can be clad with a metal from the 1000 or 6000 series to provide protection of the core material. Alloy 6061 is the most popular alloy and is commonly used in aircraft construction. Besides that, the alloying elements in 6XXX group are magnesium and silicon in approximately equal proportions. Heat treating forms the hardening compound magnesium-silicide. The group provides alloys of moderate strength, good workability, and good corrosion resistance. Many extrusions are made from this series. Zinc is the major alloying element in 7XXX group. When small amounts of magnesium are treated, very high strengths can be achieved. 7075 is one of the highest strength aluminum alloys and is used in aircraft applications. The seven major groups, 1xxx through 7xxx, can be further broken down into two subdivisions based on the manner in which they are strengthened. The common alloys are those, which are non-heat treatable and are hardened only by the amount of strain hardening such as cold work. They cannot be strengthened by heat treatment. Heat treatment will only soften common alloys. The common alloys are in the 1xxx, 3xxx, 4xxx, and 5xxx series. The hard alloys are those, which are hardened by heat treating. The heat treatment normally includes a high temperature heating, quenching, and re-heating at a lower temperature. The hard alloys are in the 2xxx, 6xxx, and 7xxx series.

## 2.8 Aluminum Alloy Series System

A system for designating wrought aluminum and wrought aluminum alloys was established by the Aluminum Association. Specific limits for chemical composition to which conformance is required are provided by applicable product standards. A system of four-digit numerical designations is used to identify wrought aluminum and wrought aluminum alloys (TENNALUM ISO 9002 Article, 2002).

| Material | Series |
|---|---|
| 1) Aluminum, 99.00% minimum and greater | 1XXX |
| 2) Copper (Cu). | 2XXX |
| 3) Manganese (Mn) | 3XXX |
| 4) Silicon (Si) | 4XXX |
| 5) Magnesium (Mg) | 5XXX |
| 6) Magnesium and Silicon (Mg and Si) | 6XXX |
| 7) Zinc (Zn) | 7XXX |

**Table 2.1**: The major alloying elements grouped of aluminum alloy

For 1XXX series group, it is aluminum purities with 99.00 percent and greater, the last two of the four digits in the designation indicate the minimum aluminum percentage. These digits are the same as the last two digits to the right of the decimal point in the minimum aluminum percentage when it is expressed to the nearest 0.01 percent. The second digit in the designation indicates modifications in impurity limits (P.J. Gregson and S.J. Harris, 2000). If the second digit is zero, it indicates unalloyed aluminum having natural impurity limits; integers 1 through 9, which are assigned consecutively as needed, indicate special control of the of more individual impurities or alloying elements.

### 2.8.1 Temper Designation System

The temper designation system is used for all forms of wrought and cast aluminum and aluminum alloys except ingot. It is based on the sequence of basic treatments used to produce various tempers. The temper designation follows the alloy designation with the two separated by a hyphen. Basic designations consist of a letter while subdivisions of those basic tempers, where required, are indicated by one or more digits following those letters. The system is designed to set down specific sequences of fabrication processes, but only those operations that are recognized as significantly influencing the characteristics of the product involved (Matweb Material Data Property, 2000). Should some other variation of the same sequence of basic operations be applied to the same alloy, resulting in different characteristics, the additional digits will be added to the numerical designation.

### 2.8.1.1 Basic Temper Designations

The **Table 2.2** below had shown the code and it condition of temper designations for aluminum alloy.

| Code | Condition |
|---|---|
| **F** | **As fabricated.** Denotes metal that has been fabricated to ordered dimensions without any attempt on the part of the producer to control the results of either strain-hardening operations or thermal treatments. There are no mechanical property limits, and the strength levels may vary form lot to lot and from shipment to shipment. |
| **O** | ***Annealed.*** Applies to wrought products that have undergone a thermal treatment to reduce their mechanical property levels to their minimums. Often described as "dead soft" metal. |
| **W** | ***Solution heat-treated.*** An unstable temper applying to certain of the (7XXX) heat-treatable alloys that, after heat treatment, spontaneously age harden at room temperature. Only when the period of natural aging is indicated (W 1hr. for example) is this a specific and complete designation. |
| **H** | ***Strain-hardened.*** Applies to those wrought products which have had an increase in strength by reduction through strain-hardening or cold working operations. The "H" is always followed by two or more digits. |
| **T** | ***Thermally treated to produce tempers other than F, O or H.*** Applies to those products which have had an increase in strength due to thermal treatments, with or without supplementary strain-hardening operations. The "T" is always followed by one or more digits. |

**Table 2.2:** Basic temper designation

### 2.8.1.2 Temper Codes Designation

From **Table 2.3**, it shown the explanation of temper codes and it condition for aluminum alloy system.

| Temper Codes | Description |
|---|---|
| T1 | Cooled from an elevated temperature shaping process and naturally aged to a substantially stable condition. |
| T2 | Cooled from an elevated temperature shaping process, cold worked, and naturally aged to a substantially stable condition. |
| T3 | Solution heat treated, cold worked, and naturally aged to a substantially stable condition. |
| T4 | Solution heat treated, and naturally aged to a substantially stable condition. |
| T5 | Cooled from an elevated temperature shaping process then artificially aged. |
| T6 | Solution heat treated then artificially aged. |
| T7 | Solution heat treated then and overage/stabilized. |
| T8 | Solution heat treated, cold worked, and then artificially aged. |
| T9 | Solution heat treated artificially aged, and then cold worked. |
| T10 | Cooled from an elevated temperature shaping process, cold worked, then artificially aged. |

**Table 2.3:** Temper codes designation

The temper designation system is used to specify the condition, or temper, of a heat treatable alloy. The most common designations include O (sometimes erroneously referred to as TO), F, T4 and T6. O refers to soft or annealed condition and is the preferred temper for forming processes such as tube bending. F refers to the condition of the material following a forming process during which work hardening occurs, and is the official designation of tubing bends. T4 designates that the alloy was solution heat treated and naturally aged. T6 is sometimes referred to as fully heat treated and is the result of solution heat treating and artificial aging.

## 2.9 Precipitate Free Zones

Precipitate Free Zones are process which all age hardening alloys contain regions adjacent to the grain boundaries which are depleted of precipitates of zones or region. This region is called **Precipitate Free Zones**. The result from depletion of both vacancies and solute it in this region. Because of that wide of PFZs are not proposing with reason it affects to the mechanical and corrosion properties of the alloy. So, the heat treatment processes are designed to minimize the narrow PFZs (www.aluminium.matter.uk).

**Figure 2.1** below had shown the microstructure about hypothetical vacancy concentration profile around the grain boundary of the aluminum alloy.

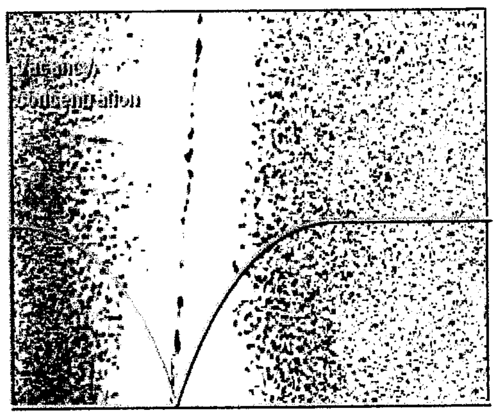

**Figure 2.1:** Hypothetical vacancy concentration profile around the grain boundary

**Figure 2.2** below had shown the critical concentration of the vacancies necessary for precipitate nucleation at temperature T for aluminum alloy.

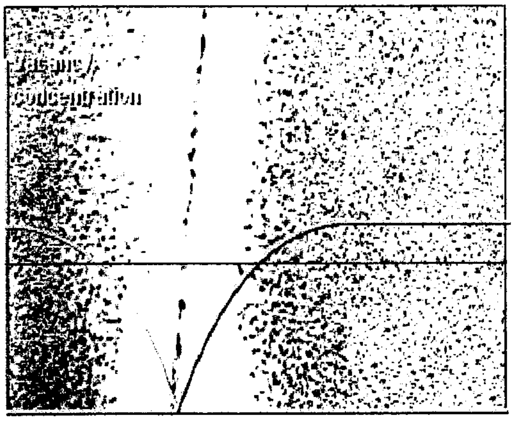

**Figure 2.2:** Let C1 be the critical concentration of vacancies necessary for precipitate nucleation at temperature T.

Besides that, **Figure 2.3** had shown the area close to the boundary where the vacancy concentration is less than C1 precipitates.

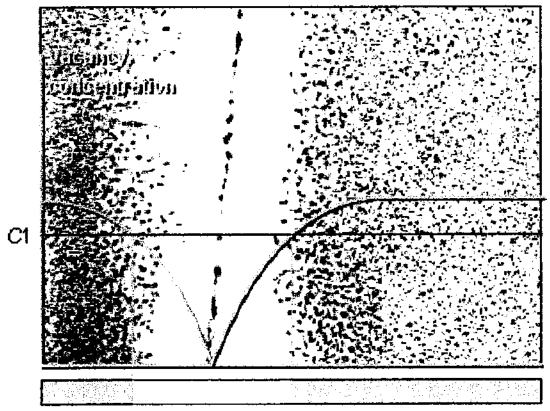


**Figure 2.3:** In the area close to the boundary where the vacancy concentration is less than C1 precipitates do not form

**Figure 2.4** below also described the mechanism of increasing overall vacancy concentration to reduce the width of PFZ.

C1

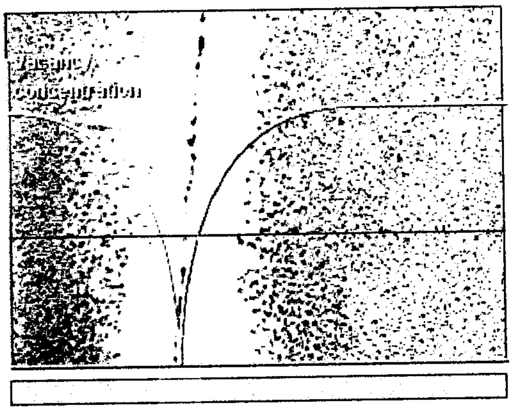

**Figure 2.4:** By increasing overall vacancy concentration (altering process variables) the PFZs can be reduced.

**Figure 2.5** below had shown the microstructure during aging at lower temperature T2 to reduce the vacancy concentration near the grain boundary.

C1
C2

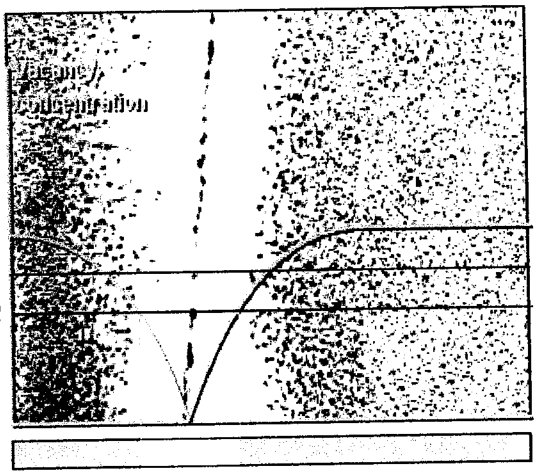

**Figure 2.5:** Ageing at lower temperature T2 reduces the critical vacancy concentration and hence PFZ width.

It is often the case that precipitation does not occur uniformly throughout the microstructure during the heat treatment of a supersaturated phase. Regions in the proximity of a grain boundary are frequently found to be free of precipitates. These precipitate free zones (or PFZ's) occur for two reasons (H. K. D. H. Bhadeshia, Cambridge 2000). The most common reason for the formation of PFZ's is that precipitates nucleate heterogeneously on vacancies. A grain boundary is a sink for vacancies so that regions adjacent to the boundary are unable to nucleate the precipitates, even though the matrix may be supersaturated with solute. The grain boundaries themselves are potent heterogeneous nucleation sites. Particles may nucleate first at these boundaries, thereby removing sufficient solute from the adjacent matrix. The solute-depleted region in the proximity of the boundary therefore remains precipitate-free. More details can be found in.

### 2.9.1 Direct Evidence for Vacancy Depletion at Grain Boundaries

As stated above, excess vacancies tend to sink into grain boundaries, but if these boundaries are few and far between, then they can also precipitate as dislocation loops. The electron micrograph below shows a grain boundary and dislocation loops formed by the condensation of vacancies. There is a loop-free zone adjacent to the boundary, because the excess vacancies have sunk into the boundary instead of condensing into dislocation loops.

## 2.10 Wear Resistance

Wear appears to be an inevitable consequence of relative motion between solid bodies and is fundamentally related to the nature of contact between solid bodies. Profilometry studies have revealed that almost all surfaces of solid body are rough where perhaps the only known exception is perfectly cleaved faces of a single crystal. Artificial smoothing and polishing of surfaces only reduces the scale of roughness and cannot create a truly smooth or planar surface. Surfaces of real objects are composed an irregular series of peaks and troughs and when two solids bodies are pressed together, true contact is limited to the peaks of surface roughness which are known asperities.

Direct experience of wear and the importance of controlling it are probably as old as the invention of the wheel and axle. Ancient civilizations were familiar with failure of axles by wear and devised rudimentary lubricants to suppress the wear. Prehistoric cavemen in northern country probably resented the fact that their primitive foot coverings of un-tanned animal skin were rapidly destroyed by wear. An adequate description of what wear is fundamentals causes and mechanisms are in contrast only a recent discovery. A primary reason for this historical delay in understanding is that the collection of experimental evidence of wear mechanism relies on sophisticated microscopes and surfaces profilometry, which were only developed not so long ago (Daniel and Alan W. Pense, 2000).

### 2.10.1 Wear Resistance of Aluminum Alloy

Aluminum alloy has high wear resistance, good corrosion resistance and good machinability. It is particularly suitable for shaped articles used at below 150° C. The invention relates to an aluminum alloy in extruded form with high wear resistance, good corrosion resistance and good machinability. The invention also relates to a method for manufacturing such aluminum alloy and, in addition, to the use of the aluminum alloy in shaped articles such as pistons for braking systems and pneumatic valves, particularly articles used not above 150° C. For products which are suitable for use in applications demanding high wear resistance, for example pistons in a breaking system, aluminum alloys such as AA6262 and AA6061 are often used, which products are then provided with a hard, wear resistant surface layer, applied by hard anodization. Such a hard anodization layer is also quite resistant to corrosion. A disadvantage is that the application of an anodization layer is an additional process step, which is moreover expensive and thus has the effect of raising costs. Another disadvantage is that the anodization process is damaging to the environment. A further disadvantage is that for many applications, a good wear resistance and a good corrosion resistance are certainly important, but the results that can be obtained with a hard anodization layer are often much better than is necessary for the applications involved (A.W. Batchelor, Loh Nee Lam 2000).

The addition of Cu to an aluminum alloy 6XXX series generally leads, after heat treatment, to an increase in the mechanical properties of the alloy concerned, such as an increase in the tensile strength. Where there is an increasing Cu-content in the alloy, the corrosion resistance decreases, in particular the corrosion resistance in a chloride-containing environment decreases rapidly with an increasing Cu-content. In view of a number of applications in a corrosive environment, in order to achieve a good corrosion resistance in the aluminum alloy in accordance with the invention, preferably there is deliberately no Cu added to the alloy other than that is coincidentally or unavoidably present in the scrap used. The Cu-content in the alloy must be below 0.35 weight % and the resistance to corrosion is particularly good if the Cu-content is lower than about 0.1%. The extruded aluminum alloy in accordance with the invention can be supplied as rods or other extruded shapes in various heat treated conditions, so-called tempers, after which it can be processed into products for a wide range of applications, where a hard anodizing step may not be required, a sufficiently wear-resistant surface layer being present. The rods can be for example round rods, hexagon rods, flat rods, solid sections or hollow sections. The rods are supplied in for example any of the tempers from the series T3, T351, T4, T451, T5, T6, T651, T8, T851, T9, etc., or an O temper as they are mentioned in Aluminum Standards and Data, published in 1988 by The Aluminum Association and incorporated herein by reference (United States Patent 5853508 Article).

**Table 2.4** below lists the results of the wear tests, according to the well-known "pin-on-disk" method. Test conditions were: alloy condition T8; surface of the "pin": 100 $mm^2$; "disk" material: 110 Cr6 with a hardness of 58 HRC. Afterwards, in the non-lubricated tests: running speed 0.25 m/s for 20 hrs; air temperature 20°-25° C.; relative air humidity 40-60%. For the lubricated tests: running speed 0.01 m/s for 20 hrs; lubricating substance: undoped oil, BP Transcal M; temperature 40° C. The wear behavior is expressed as a so-called "wear-rate" with, as unit, $m^3$ / Nm and is dependent upon the pressure exercised in N during testing.

| | Non-lubricated | Lubricated | |
|---|---|---|---|
| Alloy | 50 N | 500 N | 1000 N |
| 1 | $54 \times 10^{-15}$ | $0.61 \times 10^{-15}$ | n.t. |
| 2 | $52 \times 10^{-15}$ | $0.16 \times 10^{-15}$ | n.t. |
| 3 | $70 \times 10^{-15}$ | n.t. | n.t. |
| 4 | $57 \times 10^{-15}$ | $0.41 \times 10^{-15}$ | n.t. |
| 5 | $43 \times 10^{-15}$ | n.t. | $0.11 \times 10^{-15}$ |
| 6 | $47 \times 10^{-15}$ | $0.52 \times 10^{-15}$ | $0.25 \times 10^{-15}$ |
| 7 | $50 \times 10^{-15}$ | $0.73 \times 10^{-15}$ | $0.31 \times 10^{-15}$ |
| 8 | n.t. | n.t. | n.t. |

**Table 2.4:** Wear Test result various type of alloy

From these results, it can be seen that the alloys 6, 7, and alloy 5, in particular, by comparison with the comparative materials, combine good mechanical properties of alloy.