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# Influence of Heat Treatment on the Mechanical Properties of Aluminium Alloys (6xxx Series): A Literature Review

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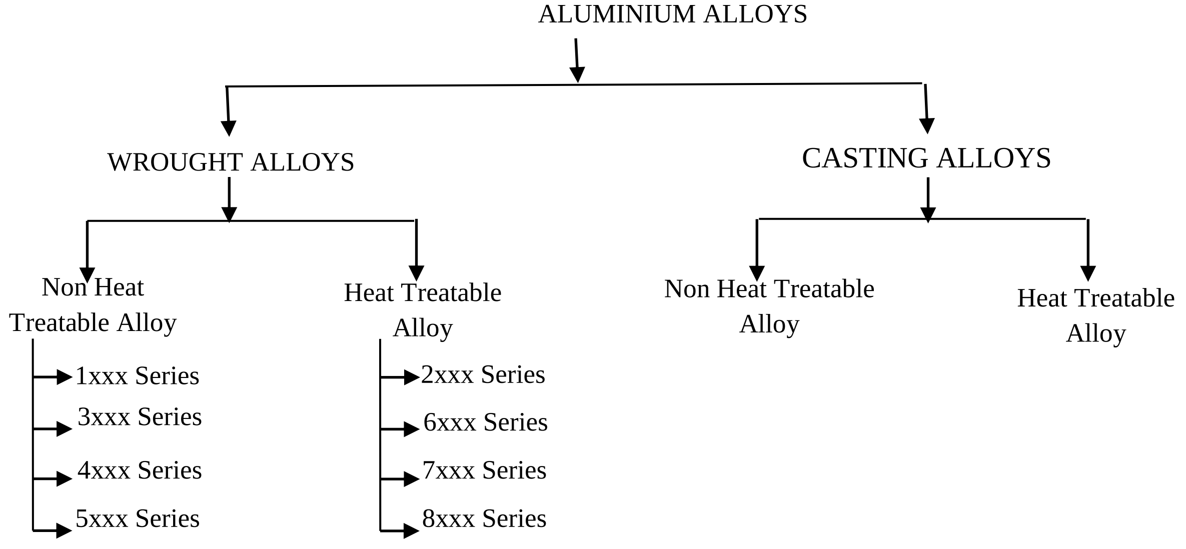
***Abstract* - This paper shows the literature survey on influence of heat treatment on mechanical properties of most widely used heat treatable aluminium alloy of 6xxx series also known as aluminium-magnesium-silicon (Al−Mg−Si) alloys. Aluminium alloys are among the easiest of all materials to form and machine. The mechanical properties are enhanced by alloying different elements or precipitation hardening or strain hardening by cold working. Alloys in the 6xxx series contain silicon and magnesium approximately in the proportions required for formation of magnesium silicate ($Mg_2Si$), thus making them heat treatable. 6xxx series alloys have good formability, weldability, and machinability. These are used in manufacturing of pipes, railings, furniture, architectural executions, automotive parts and medical equipments. Some commonly used aluminium alloys of 6xxx series are 6005, 6061, 6063, 6082 alloy. The parameters of heat treatment which significantly affect the mechanical properties of aluminium alloy are investigated through literature survey in this paper.**

## I. INTRODUCTION

Some outstanding attributes like good workability, corrosion resistance, good electrical and thermal conductivities, low density, high ductility, reasonably high strength, relatively low cost etc. make aluminium alloy one of the most versatile engineering materials. Pure aluminium and its alloys have the face-centered cubic (FCC) structure, which is stable up to its melting point at 657 °C. Aluminium contains multiple slip planes; this crystalline structure greatly contributes to the excellent formability of aluminium alloys.

The most important property of aluminium is its light weight having density 2.7 g/cm$^3$, which is about one-third of steel. Another important property of aluminium is high electrical and thermal conductivity which is about 62 percent that of copper. Aluminium has good formability, workability and castability. It can be hammered, forged and can be drawn to any shape and size. Aluminum alloy has excellent casting properties like low melting point, high degree of fluidity in molten stage and low shrinkage on solidification.

Some alloys respond to thermal treatment based on phase solubilities. These treatments include solution heat treatment, quenching, and precipitation or age hardening, for either casting or wrought alloys, such alloys are described as heat treatable. There are two classifications, namely casting alloys and wrought alloys, both of which are further subdivided into the categories heat-treatable and non-heat-treatable.



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*Al-Mg-Si alloys (6xxx series)* – Alloys in the 6xxx series contain silicon and magnesium approximately in the proportions required for formation of magnesium silicate ($Mg_2Si$), thus making them heat treatable. 6xxx series alloys have good formability, weldability, machinability, and corrosion resistance. 6061 alloy is one of the most commonly used general purpose aluminium alloys. Some other alloys of this series are 6005, 6061, 6063, 6082. The alloy 6005 is used in structural applications, 6060 has better extrudability, 6061 is most versatile of heat treatable group having good corrosion resistance which is used in transportation and structural applications and 6063 is most popular extrusion alloy. The chemical composition of some commonly used Al alloys is as shown in table:

| Alloy | Si (%) | Mg(%) |
|---|---|---|
| 6005 | 0.60 - 0.90 | 0.40 – 0.60 |
| 6063 | 0.20 – 0.60 | 0.45 – 0.90 |
| 6061 | 0.40 – 0.80 | 0.80 – 1.2 |
| 6106 | 0.30 – 0.60 | 0.40 – 0.80 |
| 6082 | 0.70 – 1.3 | 0.60 – 1.2 |

Table 1: Percentage Chemical Composition

*Heat Treatment of Aluminium 6xxx Alloys*

The 6000 series alloys are typical heat-treatable aluminium alloys which gain their strength from thermal processing rather than mechanical deformation. The key elements of these alloys are magnesium (Mg) and silicon (Si) which combine to form the $Mg_2Si$ precipitates. These precipitates occur in several forms which may be divided into the following three categories;

Coherant Precipitates [β" (beta double prime) $Mg_2Si$] - The smallest type of $Mg_2Si$ precipitate that is rod shaped, contributes most to mechanical properties when densely dispersed.

Partially Coherant [β' (beta prime) $Mg_2Si$] - A larger version of rod-shaped precipitate that grows from the β" category. The β' precipitates have a negligible contribution to mechanical properties.

Incoherant Precipitates [β (beta) $Mg_2Si$] - The largest $Mg_2Si$ precipitate that is cube-like in shape, due to its size contributes nothing to mechanical properties.

All of these alloys of 6xxx series are heat treatable by precipitation hardening. This involves two steps—solution heat treating and aging. Solution heat treatment is done by raising the alloy temperature to about 580°C and holding it there for about one hour. The purpose of this is to dissolve all the alloying elements in a solid solution in aluminum. Then the alloy is quenched in water. The purpose of quenching isn't really to strengthen the alloy, although it does somewhat; it is to cool it rapidly enough to prevent the alloying elements from precipitating on cooling. So we have a solid solution of magnesium, silicon, and other elements in aluminum at room temperature. This is called the T4 temper. If we take this material and heat treat it at a temperature between 150°C and 200°C, the alloying elements begin to form ordered arrays of atoms in the aluminum matrix. These arrays are called GP zones, and they strengthen the aluminum considerably. This heat treatment is called aging, which results in material with a T6 temper.

## LITRATURE REVIEW

*Qiang R.G.*: et al [1] performed experiments to study the influence of aging conditions on the microstructure and tensile strength of aluminium alloy 6063. Three pre-aging conditions were considered (i) 288 h natural aging (aging at room temperature (RT); (ii) 3 h natural aging; and (iii) 3 h natural aging plus 5 h aging at 80°C, The specimen were subsequently aged at 165°C, 185°C and 205°C from 0.25 to 64 h. Tensile tests and microstructure study were performed using transmission electron microscopy (TEM) and atom probe field ion microscopy (APFIM). It was concluded that (for specimen with the same pre-aging condition) the higher subsequent aging temperature lowers the peak strength.

*Cheng L.M.*: et al [2] investigated the influence of precipitation on the work-hardening behavior of the Aluminium Alloys AA6111. In order to examine the influence of precipitation state on yield stress and work-hardening behavior the tensile tests were conducted on the aluminium alloy AA6111 after various artificial aging treatments.

*Grazyna Mrowka-Nowotnik*: et al [3] investigated the influence of aging duration on hardness of Al 6005 and 6082 alloy. The microstructure changes of the aluminium alloys following aging for 120 h were investigated by metallographic observations. Al 6005 and 6082 samples were preheated in induction furnace at temperature 570°C and hold for 4 to 6 h and then cooled using different cooling rates (quenching in water, oil and air cooling or slow furnace cooling). Water cooled samples were subjected to T4 (solution heat treatment and natural aging). The influence of solution heat treatment temperature on 6005 and 6082 alloys was investigated from temperature range 510°C to 580°C and then natural aging in the room temperature to 120 h. The Tensile and Brinell hardness

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tests were conducted. It was observed that hardness of the 6082 alloy increases with increasing heat treatment temperature. It was concluded that solution temperature does not affect the hardness of 6005 alloy. It was concluded that the hardness of 6082 alloy was more sensitive to cooling conditions then to the duration of homogenization.

*Halil Demir*: et al [4] studied the effect of artificial aging on machinability of 6061 aluminium alloy. Three different types of samples (the non heat treated, solution heat treated and solution heat treated with aging) were machined. Samples were solution heat treated at 530°C for 4 h followed by quenching in water at room temperature. The samples were placed in freezer to avoid natural aging. The workpieces were artificially age hardened at 180 º C for a period of 1, 5, 11 and 24 h in a furnace and subsequently cooled in air. It was concluded that in turning process cutting speed significantly affects the surface roughness of machined surface.

*Tan*: et al [5] considered aluminium alloy 6061-T6 to determine the effect of artificial aging on the hardness. In artificial aging the temperature variation was between 175°C to 420°C at different period of time. The Vickers hardness test was performed to evaluate the effect of heat treatment on hardness of aluminium alloy 6061-T6 before and after aging process. The optimum aging time and temperature was determined at the end of this experiment to obtain reduction in energy and total cost. It was concluded that the optimum aged was achieved between 175°C to 195°C with 2 to 6 h of aging time.

*Chang*: et al [6] observed that natural pre-aging has a positive effect on artificial aged Al−Mg−Si alloys. The study leads to the conclusion that natural aging increases the volume fraction of fine precipitates and significantly improves the mechanical properties.

*Mansourinejad*: et al [7] investigated the influence of combination of different designated precipitation hardening processes and cold working on the tensile properties of 6061 aluminum alloy. In order to study the influence of various sequences of cold working and age hardening on mechanical properties, different series of thermal mechanical treatments were utilized. In this experimental set up aging conditions (pre-aging, single and double aging) and extent of reduction in area were the important features of investigation. All samples were solutionized at 520°C for 1 h and then quenched immediately in water. Cold working was conducted by rolling mill to the reduction of 20%, 40% and 60% in area. The result indicated that applying single aging at 180°C for 4 h in different thermal-mechanical treatments improved both the strength and elongation.

*Aytekin Polat*: et al [8] investigated the influence of artificial-aging temperature and time on mechanical properties and spring back behavior of AA6061. All the 6061 Al-alloy specimens, except those in the as-received condition, were solution heat treated at 550°C for 2 h followed by quenching in water at room temperature. After the solution heat treatment, all the AA6061 samples were kept in a refrigerator to avoid natural aging of the alloy at room temperature. Following the solution heat treatment, the specimens were artificially age hardened in a furnace at (160°C, 180°C, and 200°C) for periods of 2.5, 5, 10, 20, 40, 60, and 80 h and subsequently quenched in water. Tensile tests were performed at room temperature.
It was observed that the peak-strength values of the alloy for the aging temperatures of (160, 180 and 190)°C were obtained when the alloy was aged for 60, 10 and 5 h, respectively. The aging between 5 h and 40 h at 180°C was the most suitable combination of duration and temperature exhibiting the maximum hardness, yield strength and tensile strength of the alloy. A decrease in the mechanical properties of the alloy in over-aging conditions (an increase in the artificial-aging temperature and time) occurred because of the coalescence of the precipitates into larger particles, a bigger grain size and also due to the annealing of the defects. The results revealed that the yield strength, the tensile strength and the elongations decreased with the increasing artificial-aging temperature but increased with the increasing artificial-aging duration up to the peak age.

*Shivakumara.P*: et al [9] performed experiments on commercial grade Al 6061 alloy for investigations. The Al 6061 alloy was subjected to solution heat treatment at a temperature of 540°C for 2 h followed by quenching in water. The quenched specimen was subjected to artificial aging. Tensile test and hardness tests were conducted on the specimen subjected to heat treatment. It was observed that (under identical heat treatment conditions) Al 6061 subjected to heat treatment under T6 conditions exhibited a significant improvement in hardness when compared with Al 6061 before heat treatment. The mechanical and structural properties of Al6061were improved after heat treatment. Tensile strength and hardness of Al 6061 was increased with the increase in aging time. The elongation of specimen decreased with heat treating and aging.

*Abd M.E. El-Azim*: et al [10] investigated the artificial aging behavior of 6061 alloy on hardness and tensile properties by varying the aging temperature from 120°C to

260°C and aging time from 0.5 to 64 h. The natural aging for 100 h followed by artificial aging resulted higher yield and ultimate tensile strength. Pre-aging at 100°C for 5 min followed by artificial aging at 160°C for 18 h(peak aged condition) resulted in higher yield strength and ultimate tensile strength as compare to artificial aged samples only.

## II. CONCLUSION

From literature survey it is concluded that there are two factors which significantly influence the mechanical properties one is proportion of alloying elements and second is age hardening process parameters.

The alloying elements have significant influence on mechanical properties. In the alloying elements like 6061, 6063 there is excess of Mg and in the alloying element 6082 there is excess of Si. The excess of Mg and Si increases the strength and hardness and reduces ductility and toughness Aluminium alloy 6005 have better tensile and yield strength than other alloying elements of this series. The order of tensile and yield strength for various alloys of this series is *6005 > 6106 > 6063 > 6061*.

The heat treatment process parameters have significant influence on mechanical properties. Following are some important conclutions:

- Natural pre-aging has positive effect on artificial aged Al−Mg−Si alloys and improves mechanical properties.
- The yield strength, tensile strength and elongations decreases with the increasing artificial-aging temperature. While machining 6061 aluminium alloy cutting speed significantly affects the machined surface roughness.
- The mechanical and structural properties of Al 6061 are improved after heat treatment. Tensile strength and hardness of Al 6061 was increased with the increase in the aging duration.
- For aluminium alloy 6063 (with the same pre-aging condition) the higher subsequent aging temperature lowers the peak strength.
- Hardness of the 6082 alloy increases with increasing heat treatment temperature. Hardness of 6082 alloy is more sensitive to cooling conditions then to the duration of homogenization.

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