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Modification of Mechanical & Metallurgical properties of Aluminum Alloy through Heat treatment

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Abstract– The mechanical and metallurgical properties of heat treatable aluminum alloys are significantly improve by various heat treatment processes. Some heat treatable aluminum alloys used for various industrial applications are designated as 2xxx, 6xxx, 7xxx series etc. Various process parameters of heat treatment processes significantly affect the mechanical properties of aluminum alloys. The mechanical properties of heat treatable aluminum alloys can be modified by selecting proper heat treatment process parameters. A broad literature review is performed to investigate significant conclusions for making heat treatable aluminum alloy more suitable for particular applications and thus making them more versatile.

1. Introduction

Aluminum is a light weight material having density approximately one third of density of stainless steel. Other important properties of aluminum are high electrical conductivity and high thermal conductivity, which is about two third of copper. Aluminum has good formability, machinanability 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 after solidification. These properties make aluminum alloys as one of most widely used engineering material, suitable for various applications. Allunimium alloys are classified as heat treatable and non heat treatable, depending upon weather the alloy responds to precipitation hardening or not. Some alloy designated as 2xxx, 6xxx, 7xxx are common examples of heat treatable alloys and are widely used for various applications. The heat treatable alloys show the greater solubility at high temperature as compare to room temperature. These alloys respond to thermal treatment based on phase solubility. These treatments include solution heat treatment, quenching, and precipitation hardening or age hardening.

Table No.1 represents various series of heat treatable and non heat treatable alloys with their major alloying element of each group

Table No.1

Non Heat Treatable Alloy	Heat Treatable Alloy
1xxx Series- Alost pure Aluminum (99.0% Purity)	2xxx Series- Cu as major alloying element
3xxx Series- Mn as major alloying element	6xxx Series- Mg and Si as major alloying element
4xxx Series- Si as major alloying element	7xxx Series- Zn as major alloying element
5xxx Series- Mg as major alloying element	8xxx Series- miscellaneous composition

Some most commonly used heat treatable aluminum alloys are as under-

- **Al 2024** – it is widely used for high-strength structural applications. This alloy has excellent machinability, good workability and fair corrosion resistance.
- **Al 6082-** It is a strong alloy and called as structural Al alloys. It is used for high strength applications.
- **Al 7075-** It is well known for its excellent fatigue strength. It has good corrosion strength, high fatigue strength and can be machined in annealed condition. It is widely used for automotive parts, aerospace, bicycle components.

2. Literature Review-

Various authors performed their research work to investigate the influence of heat treatment on mechanical and metallurgical properties of heat treatable aluminum alloys in last few years.

Rahimi et.al[1] investigated the effect of stirring speed and Solution treatment followed by precipitate hardening heat treatment on microstructure and mechanical properties of Al-2024 alloy and concluded that by increasing the stirring speed the grain size of α-Al particles decreases. An improvement in hardness and compressive properties of the alloy was observed after this heat treatment

Qiang.: et al [2] performed experiments to study the influence of aging conditions on the microstructure and tensile strength of aluminum alloy 6063. Three pre-aging conditions were considered (i) natural aging for 288 hours at room temperature ; (ii) natural aging for 3 hour; and (iii) natural aging for 3 hour plus 5 hour aging at 80°C, The specimen were subsequently aged at 165°C, 185°C and 205°C from 0.25 to 64 hour. 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 conditions, higher the subsequent aging temperature, the lower will be the peak strength of Al6063 alloy.

Cheng L.M.: et al [3] investigated the influence of precipitation on the work-hardening behavior of the Aluminum Alloy 6111. In order to examine the influence of precipitation state on yield stress and work-hardening behavior tensile tests were conducted after various artificial aging treatments.

Grazyna Mrowka-Nowotnik: et al [4] investigated the influence of aging duration on hardness of Al 6005alloy and Al6082 alloy. The microstructure changes of the aluminum alloys following aging for 120 hour were investigated by metallographic observations. Al 6005 and Al6082 alloy samples were preheated in induction furnace at temperature 570°C and hold for 4 to 6 h and then cooled using different cooling rates (by quenching the specimen in water, oil, air cooling or slow furnace cooling). Water cooled samples were subjected to solution heat treatment followed by natural aging. The influences of solution heat treatment temperature on Al6005 and Al6082 alloys were investigated for temperature range 510°C to 580°C and then natural aging in the room temperature for 120 hours. The Tensile strength and Brinell hardness tests were conducted to find the influence on mechanical properties. It was observed that hardness of the Al6082 alloy increases with increasing heat treatment temperature. It was concluded that solution temperature does not affect the hardness of Al6005 alloy. It was concluded that the hardness of Al6082 alloy was more sensitive to cooling conditions then to the duration of homogenization.

Halil Demir: et al [5] studied the effect of artificial aging on machinability of Al6061 alloy. Three different types of samples (non heat treated, solution heat treated and solution heat treated followed by aging) were machined(turning). 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 work pieces were artificially age hardened at 180 ^{o} C for a period of 1, 5, 11 and 24 hours in a furnace and subsequently cooled in air. It was practically observed that during turning process, cutting speed significantly affected the surface roughness of machined surface.

Chee Fai Tan: et al [6] worked on precipitation of aluminum alloy 6061 in operation solution heat treatment followed by artificial aging to determine the effect of artificial aging on the hardness of aluminum alloy 6061. 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 aluminum alloy 6061 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 aging was achieved between 175°C to 195°C with 2 to 6 hours of aging duration.

Chang: et al [7] find 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 of alloy.

Mansourinejad: et al [8] investigated the influence of combination of different designated precipitation hardening processes and cold working on the tensile properties of Al6061 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 considered. In this experimental set up, pre-aging, single and double aging, multiple of reduction in area and order of heat treatment and cold working were the important features of investigation. All samples were solutionized at 520°C for 1 hours and then quenched immediately in water. Cold working was performed 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 hours in different thermal-mechanical treatments improved both properties strength and elongation. However, double aging does not improve the mechanical properties.

Dong Peng et.al[9] performed experiments to find effects of aging treatment and heat input on the microstructure and mechanical properties of welded joints made by Al6061 alloy and concluded that and increase in heat input increases the width of heat effective zone and grain size of Al6061alloy,and the hardness of HAZ decreases. The post weld ageing treatment improved the hardness of TIG welded joints

AytekinPolat: et al [10] investigated the influence of artificial-aging temperature and time on mechanical properties and spring back behavior of Al6061alloy. 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 solution heat treatment, all the Al6061alloy specimen 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, 180, and 200°C for periods of 2.5, 5, 10, 20, 40, 60, and 80 hours 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 is 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 of bigger grain size. The results reveal that the yield strength, the tensile strength and the elongations decreased with the increasing artificial-aging temperature, but increased with increasing artificial-aging duration up to the peak age.

Hannes Frock et.al [11] investigated the influence of short term heat treatment microstructure and mechanical properties of Al6060 alloy extrusion profiles and find the optimal parameters

Buha et al [12] investigated the influence of interrupted aging of Al-Mg-Si-Cu alloy and performed research work on Al6061 alloy is one of the most extensively used Al-Mg-Si alloys and concluded that the peak-strength condition that are obtained at the temper designated T6.

Braun et al [13] worked on Stress Corrosion Cracking behavior of 6XXX Series aluminum alloys. The natural aging condition were obtained through three steps: First of all solution treatment was executed at 527° C for 1 h, then quenching was implemented immediately after the solution heat treatment and lastly, the alloys remained in the room temperature at least two days.

Seung-Jun Lee et .al [14] investigated the effects of maintaining temperature in annealing heat treatment for an Al6061 alloy and concluded that optimum annealing temperature for Al6061 alloy is 200-225° C. The heat treatment which are usually performed in the 7XXX series are solution heat treatment followed by aging. To achieve the advantages of precipitation hardening process, it is essential to produce a solid solution. The process by which it is performed is called solution heat treatment.

Xiu-TangZou et.al [15] suggested that care must be taken not to attain eutectic melting temperature of the material. If eutectic melting occurs as a result of overheating, properties such as tensile strength, ductility and fracture toughness may be disturbed so the temperature range in the solution treatment for aluminum is fixed between 440 °C to 560 °C to preserve solid solution formed at the solution heat- treating temperature. The main purpose of solutionizing is to solutionize the maximum quantity of alloying elements that are present in particular alloy. **Tash** et.al[16] concluded that the selection of quenching media depends upon to contain solid solution formed at the solutionizing temperature. These quenched samples are then subjected to precipitation hardening (aging treatment) from 120 to 200 °C for 5 to 6 hours and then followed by air cooling or water cooling on room temperature. Age hardening treatment can improve yield strength, ultimate tensile strength and hardness value but it curtails the ductility and impact strength of the material

Srinivasamurthy et.al [17] suggested a new process known as double aging, having two step aging treatment including solutionizing and then quenching , heating the alloys to a temperature lower than the solutionizing and pre-aging for a given time and finally aging at either the same or at a different temperature from the first aging treatment. It was finally concluded that dual aging process can enhance hardness and tensile values and these processes are subjected to commercially on a large variety of non ferrous materials too.

Jaburea et.al[18] investigated the influence of retrogression and re-aging treatment on the mechanical and micro structural characteristics of the aluminum alloy (Al-Zn-Mg) and concluded that the precipitation structure and mechanical properties are mainly influence by retrogression annealing.

Itsaree et.al [19] find that in Al7075 alloy over aging created low stress corrosion cracking strength but with loss of mechanical strength.

Karaaslan et.al [20] investigated that retrogression and re-aging treatments improves the stress corrosion behavior of the alloy.

Jin-feng et.al [21] concluded that the retrogression temperature is dominant controlling factor and a higher retrogression temperature enhances the dissolution degree and promotes the formation of more stable precipitates on raging.

Aliyah et.al [22] investigated the effect of heat treatment on the micro structure of Al 7075 alloy and concluded that heat treatment at temperature 300-600 °C provides significant impact on micro structural transformation.

Hement Panchal et.al [23] concluded that annealing treatment of Al 7075 alloy results the higher ductility and impact strength but it lowers ultimate tensile strength and yield strength.

Biplab Hazra et.al[24] increased the elevated temperature wear resistance of Al-Si-Cu alloy after a novel short duration heat treatment at a elevated temperature 100°C

Yaoxiang Geng et.al[25] investigated the influence of process parameters and aging treatment on the microstructure and mechanical properties of AISI8Mg3 alloy fabricated by selective laser melting and find that after aging treatment at 150C the mechanical properties of sample were improved.

V.V.Teleshov, et.al[26] worked to find influence of chemical composition on the strength of alloys of the Al-Cu-Mg-Ag system after heating at 180-210°C. It was observed that silver addition in amount of 0.5% increases the strength of Al-Cu- Mg-Ag alloy.

Lumley et .al [27] investigated the role of alloy composition in the heat treatment of aluminum high pressure die casting and concluded that when heat treated to T-4 temper develops increase in proof stress around 30%. During solution treatment Si produces significant morphological changes and Si particles provide significant strengthening of the alloy. Copper promotes a strong response to heat treatment and zinc additions have little effect on increase in tensile properties of aluminum alloys

Too Lu et.al[28] performed experimental work to find effects of Lanthanum addition on the microstructure and tensile properties of Al-Si-Cu-Mg casting alloys and find that La addition contributed to the appreciable increment in ultimate tensile strength and increased elongation

Ying Pio Lim et.al[29] studied the effect of Heat Treatment on gravity die casting aluminum alloy Al356.

Khalil Ganjehfard et.al[30] investigated the susceptibility of cast Al-Cu alloys having excess Fe and Si for tensile strength and hot tearing and find that the tensile properties of alloy were optimal when Fe –Si mass ratio was unity.

3. Analysis and Discussions

Various researches used different heat treatment processes in various sequences and used variations in the process variables for improvement of mechanical and metallurgical properties of heat treatable aluminum alloys and obtained optimum results. Some commonly used sequences of heat treatment processes by various researchers are as follows:

Solution Heat treatment followed by Natural Aging

In this process, the cast components were heated up to temperature just below the melting point of alloy and held at the temperature for a sufficient duration followed by quenching in water or boiling water or in polymer. The temperature up to which the component were heated, depends upon chemical composition of that particular alloy and the holding duration depends upon composition of alloy and cross section area of cast components. Quenching was done in appropriate medium as water or polymer. The selection of quenching medium depends upon the desire mechanical properties and managing the distortion. After solution treatment the elements which remain in dissolved state will begin to precipitate out with time. As a result of this there is improvement in the mechanical strength of aluminum alloy. Various researches concluded that the natural aging increases the hardness at room temperature and the duration varies from 4 days to 5days.

Precipitations Harding or Artificial Aging

It was observed by various researchers that some aluminum alloys did not produced good results during natural aging at room temperature as a result of this the desired value of hardness cannot be achieved. This problem was solved by precipitations hardening at higher temperature than the ambient temperature. Artificial aging was carried out above ambient temperature varying between 150-200°C and the holding duration varying from 2 hours to 24 hours depending upon composition of alloy and cross sectional thickness of the cast components. It was observed that the lower temperature and longer duration promoted precipitations and thus mechanical properties were improved. As a result of this process there is significant increment in yield strength and slight increment in tensile strength.

Solution treatment and stabilization

After solution treatment cast component were heated in the range 200-250°C for stabilization and homogenization of alloying elements. The temperature and duration of treatment depends upon composition of alloy and mass of cast components.

Solution treatment and precipitations hardening

Some researches performed solution treatment process followed by the precipitations hardening which produces the highest strength and improved tensile and yield strength.

Solution Treatment followed by artificially Aging and stabilization

The castings which are to be used at high temperature were treated by this method. Cast components after solution treatment were stabilized by heating the components between temperature 200-250°C.It was observed that after these processes the tensile strength lowers slightly and ductility increases.

Stress relieving and Annealing

Stress reliving was performed between 200-250°C and annealing is done around 300-400°C to increases softness of cast components and removes stresses present in cast components

Table No. 2 shows some important conclusions drawn by some researchers.

Table No. 2

S. No	Various Sequences of Heat Treatment Process	Observations & Discussions
1	Solution Treated and naturally Aged	Improvement in mechanical strength is observed. The natural aging of 4-5 days increased hardness. For Al 6082, the hardness increases with increase in heat treatment temperature.[4]
2	Artificially ageing or Precipitation Harding	For Al 6061 alloy, the machinability of heat treated alloy is found better.[5]
3	Solution Treated and stabilization	Stabilization and homogenization of alloying elements takes place significantly.
4	Solution Heat Treated and Fully Artificially Aged	For alloy Al 2024, the highest strength is obtained and this process improves tensile and yield strength.[1] For Al 6061, the optimum results were achieved by aging between 175-195 °C [6]
5	Solution Treated and Artificially Age and Stabilized	Ductility of heat treated alloy is better than untreated alloy.
6	Stress Relived and Annealed	There was significant stress removal from the components after these processes.
7	Natural Aging	For Al 6063 alloy it was observed that higher the subsequent aging more lower will be peak strength.[2] For Al-Mg-Si alloy, the natural aging increases the volume fraction of precipitates and thus improves mechanical properties.[7]

4.Conclusions-

The heat treatment process parameters and sequencing of various processes have significant influence on mechanical properties of Aluminium Alloys. Following are some conclusions drawn from this work:

- Natural pre-aging has positive effect on artificial aged Al–Mg–Si alloys and improves mechanical properties significantly.
- The yield strength, tensile strength and the elongations decreased 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 alloy can be improved after heat treatment. Tensile strength and hardness of Al 6061 was increased with the increase in the aging duration.
- For aluminum alloy 6063 with the same pre-aging condition, the higher subsequent aging temperature, the lower the peak strength and the shorter time it takes to reach peak strength.
- Hardness of the Al 6082 alloy increased with increasing heat treatment temperature and hardness of 6082 alloy is more sensitive to cooling conditions then to the duration of homogenization. Solution temperature does not affect the hardness of 6005 alloy
- Annealing treatment of Al 7075 creates the higher ductility and impact strength but it lowers ultimate tensile strength and yield strength.
- In case of Al 7075 alloy the heat treatment at temperature 300-600° C produces significant impact on microstructure and hardness of the alloy.
- Aging heat treatment (standardize as T6) of Al 7076 alloy gives best yield strength and ultimate tensile strength.
- Double aging treatment of Al 7076 alloy improves mechanical properties but reduces corrosion resistance.

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