Review on Effect of Heat Treatment on Properties of AA 2024

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Abstract

This paper reviews the effect of heat treatment on properties (Ultimate tensile strength, Hardness, Yield strength, elongation and modulus of elasticity) of AA 2024 alloy (Aluminum – Copper) under different heat treated conditions O, T4, T6. This paper involves the annealing, solution zing and the ageing process of AA 2024 alloy. This paper compares initial properties and property change after heat treatment is made to study effect of different heat treatment on material properties. In this paper the properties and application of AA 2024 alloy is presented. Also the hardness change in different quenching medium studied. The mechanism of solution zing and age hardening process is also studied in this paper. Finally conclude that there is increase in mechanical of AA 2024 alloy after performing heat treatment process.

Keywords: Heat treatment, annealing, precipitation hardening, properties, application, mechanism, microstructure

1. Introduction

There are two group of aluminium alloy: One which cannot be heat treated, and other which can heat treated. The heat treatable alloy can be hardened by the addition of certain alloying elements, such as copper, zinc, magnesium and silicon. Because of solubility and precipitation forming ability of these elements alloys can be heat treated. The process heat treatment of this alloy is consists of heating the solution above its Solidus line followed by quenching in water or other liquid solution like (oil, brine solution, polymeric solution) or aging [1].
Since 1930's the aluminum alloys are major elements use in aircraft industry because of its light weight, strength and excellent corrosion resistance [2]. AA2024 is one of the most widely used material in air craft industry aluminum 2024 is use in the airplane fuselage, the wing panes of air craft, the rudder, the exhaust pipes of air crafts, the door and floors of air plane and other aeronautic components, the seats, the engine turbines, and the cockpit instrumentation of air craft [3].
The heat treatment of metal by age hardening is possible for an alloy that show the decreasing solid solubility of at least one alloying element with decreasing temperature [4]. These alloys undergo the precipitation hardening. During the precipitation hardening process different precipitates can be obtained depending on the type of alloying element the alloy possess. This process will influence and produce different mechanical properties [5]. By using the precipitates line chart this precipitates are positioned on phase diagram, and the phases that are stable can be detected. So to obtain the good mechanical properties appropriate fabrication process should be chosen. Also, one needs to consider aging time and temperature, occurrence of deformation and the whole fabrication process to obtain best properties [6]. So the solution treatment and ageing give positive effect on the properties of material.

1.1. Classification of aluminum alloy based on heat treatment

1. Heat treatable aluminium alloy. : 2xxx, 6xxx, 7xxx
2. Non heat treatable aluminium alloy : 1xxx,3xxx,4xxx,5xxx,8xxx [7]

Temper designation
First the basic designation is based on operation performed on the alloy.
1.F, As-Fabricated: This process is applied to product which are shaped by cold working, hot working, or casting processes in which there is no special control over thermal conditions and strain hardening is required [8].
2. O, Annealed: This process is applied to wrought product which are annealed to obtain lowest-strength temper and to cast products that are re - annealed to improve ductility and dimensional stability of product [8].
3. H, Strain-Hardened (Wrought Products only): This operation shows the products which are strengthened by strain hardening, with or without supplementary thermal treatment to produce some reduction in strength [8].

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The designation of H is:
H1: only strain hardening.
H2: Strain hardening and partial annealed.
H3: Strain hardened and stabilized [9].
4. W, Solution Heat-Treated: This operation is an unstable temper operation which is only applicable to alloys whose strength is naturally changes at room temperature over a duration of months or even years after solution heat treatment [8].
5. T, Solution Heat-Treated: T is applied to alloys whose strength is stable within a few weeks of solution heat treatment [8].
T, Solution Heat treated – designation
T1 – partial solution treatment and natural aging.
T2 – Partial solution treatment, cold worked and natural aging.
T3 – Solution treatment, cold worked and natural aging.
T4 – Solution treatment and natural aging.
T5 – Partial solution treatment and artificial aging.
T6 – Solution treatment and artificial aging.
T7 – Solution treatment and Stabilized or over-aged.
T8 - Solution treatment, cold worked and artificially aged.
T9 - Solution treatment, artificially aged and cold worked.
T10 – Partial solution treatment, cold worked and artificially aged [10].

1.2. Heat treatment

Annealing and precipitation hardening is heat treatment processes for implementation of properties of heat treatable aluminium alloy [11].
Annealing: Annealing is a process which decrease the strength and hardness while increase the ductility. Annealing can used for both heat treatable and non heat treatable aluminium alloy with both grades of wrought and cast alloys. If the cold worked aluminum alloy is heated at sufficiently high temperature for long time then annealing process divided into three parts: 1. Recovery: During recovery the stresses which are produced by cold work are reduced, with decrease in strength and increase in ductility. 2. Recrystallization: During recrystallization the new undeformed nuclei form and grow until they react with each other to form a new recrystalized grain structure. 3. Grain growth: The increase in grain size of new formed recrystalized grain is grain growth process [12].
Quenching: Quenching is a process when a metal is subject to heat at a high temperature and then follow by a rapid cooling as fast as possible by immersing the heated metal in a relatively colder liquid such as oil, water, polymeric solution, air. This process increases alloy's strength and corrosion resistance. The alloy's properties are determined by the constituents present in alloy as well as its properties like its thickness and cooling rate when the alloy is quenched which depends on the type of quenching medium and temperature.
Maximum corrosion resistance can be obtained from quenching in cold water which is implemented on products manufactured by tube sheet, extrusions. Slower quenching mediums such as boiling water is implemented on large or forgings sections. Lower quenching rate has a more homogeneous cooling rate and it produces a less distorted and cracked product which usually occur from uneven cooling. The quenching medium temperature does not affect the corrosion resistance; it is observe that the corrosion resistance is less in thick or heavy parts than it is in thin parts [13].
The metal obtain high strength through the rapid cooling from the high-temperature solution followed by aging treatment. But the rapid cooling from high temperature lead to undesirable residual stresses [14]. When the heated parts are quench the quenching rate at surface of metal and center of metal produce thermal gradient which will result in inhomogeneous plastic deformation [15]. It has been noted that the residual stresses have negative effects on parts properties which cause distortion and dimensional variation result in premature failure [16]. To increase lifetime it is required to remove all the residual stresses from metal to obtain dimensional accuracy.
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1.3. Properties and applications of 2024 Al alloy:

The 2024 aluminum alloy has high strength and high fatigue resistance. This alloy has good workability and fair machinability. But, the 2024 aluminum alloy has poor corrosion resistance and poor weldability [17].

Applications: Due to its high strength and fatigue resistance, AA 2024 is widely used in aircraft, especially wing and fuselage structures under tension, floor of air craft [18]. It is also used in the hardware, truck wheels, and parts for the transportation industry [19]. Additionally, since the material is susceptible to thermal shock, AA 2024 is used in qualification of liquid penetrant tests outside of normal temperature ranges [20].

1.4. Mechanism of Precipitation Hardening of 2024:

The precipitation hardening of aluminium 2024 is quite complex process which consist different steps or say this hardening occur in sequence of formation of different precipitates. Figure 1 shows the Aluminum copper phase diagram in which the age hardening process is shown where the process consists of basic three steps: 1)Solution Treatment: The solution treatment also called as Solutionizing, is the first step in the precipitation-hardening process. This alloy has α and θ as primary phase. When this alloy is heated above the solvus temperature and soaked the (α) is produced as the homogeneous solid solution and this θ precipitates are dissolved in this step and any segregation present in the 2024 alloy is reduced. 2) Quenching: The quenching is the second step where the homogeneous solid α is rapidly cooled by water or other liquid solution. After rapid cooling this homogeneous α make supersaturated solid solution of αSS which contains excess copper and is not an equilibrium structure. The atoms in this stage do not have time to diffuse to potential nucleation sites and thus θ precipitates do not form. 3) Aging: The aging is the third step where the supersaturated solid solution of α, is heated below the solvus temperature as shown in fig. 1 to produce a finely dispersed precipitate. Atoms diffuse only short distances at this aging temperature. In this process the supersaturated α is not stable, so the extra copper atoms is diffuse to numbers of nucleation sites and the precipitates will grow. This finely dispersed precipitate in the alloy is the objective of the precipitation-hardening process. The fine precipitates in the alloy impede dislocation movement by forcing the dislocations to either cut through the precipitated particles or go around them. By restricting dislocation movement during deformation, the alloy is strengthened [10][21].

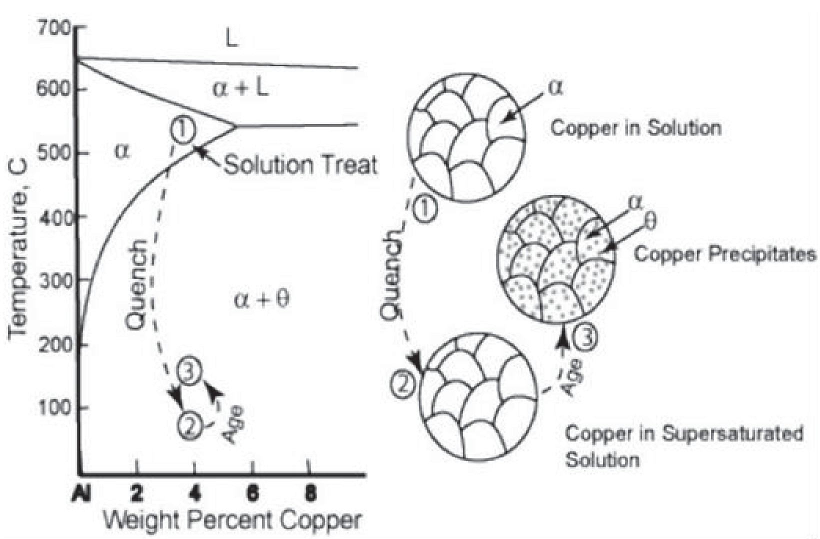

Fig. 1. Al – Cu phase diagram [22]

The age hardening process form different type of Precipitate as shown in fig. There are three type of Precipitate.

1. Coherent precipitate: The coherent precipitate is form so that there is definite relationship between the precipitates and matrix's crystal structure. This precipitates have higher hardness then other precipitates.
2. Semi coherent precipitates: This precipitates are intermediate form of coherent and incoherent type of Precipitate. This precipitates have high hardness then incoherent but lower then coherent precipitate.
3. Incoherent precipitates: This type of Precipitates does not have any relationship between precipitates and matrix crystal structure [23]

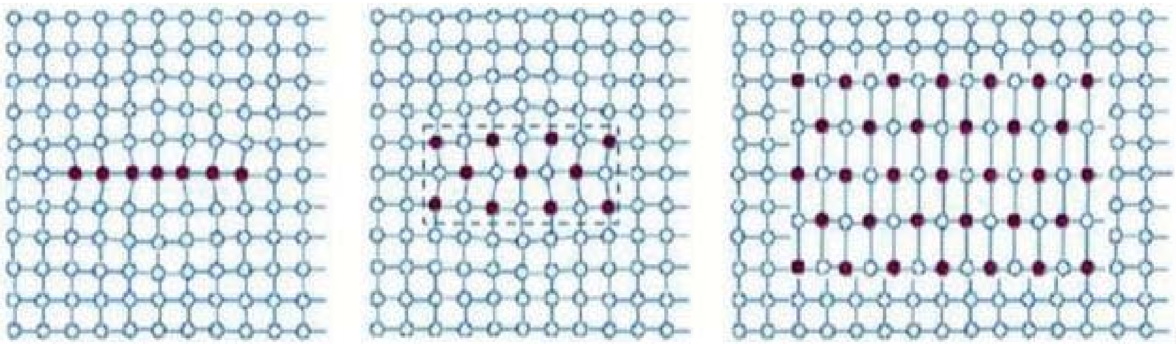

Fig. 2. Coherent, semi-coherent and incoherent precipitates [24]

The precipitation hardening process consist steps:
$a_{0\ (ssss)}$ → GP zones → θ'' → → θ' → θ [23]
GP Zone: GP zone is first stage of age hardening process. This is plate like structure of copper atom which are segregated on [100] plane of aluminum lattice. They are rapidly formed after quenching that is part of clusters formed during quenching. GP zone have coherency strain. As the atomic diameter of Cu is less than Al, elastic straining is induced as a local change in inter-planer distance as shown in fig. GP zone is called coherent precipitates with straining [25].
θ” precipitates: Earlier, it was called as GP zone–2, but experiments revealed that it has definite but different crystal structure than the matrix. Θ” is coherent type precipitates. This precipitates are in plate form of minimum thickness 100 A° and up to maximum diameter of 1500 A°. This precipitates have tetragonal structure with a=0.404 nm and c=0.768 nm as shown in Figure 3. This precipitates has ordered arrangement of Cu and Al atoms. This precipitates have higher hardness then other precipitates [25].
θ’ precipitates: These precipitates are large in diameter and can be observed under optical microscope. This precipitates are transition precipitates. This precipitates has tetragonal structure with a=0.404 nm and c=0.580 nm. As shown in fig. 3, the composition of θ’ is differ from θ” and this precipitates are semi-coherent precipitates. The elastic strain around this precipitates is small and the formation of θ’ precipitates lead to soften the alloy. So, this precipitates has lower hardness than θ” [25].
θ precipitates: This precipitates are fully incoherent precipitates. This precipitates has tetragonal structure. Formation of this precipitates always lead to soften the alloy. So, there will always lower hardness obtained in this precipitates. It nucleate heterogeneously and is more easily formed when ageing at higher temperature. This precipitates is the ultimate result of over ageing. This precipitates have tetragonal crystal structure with a=0.6066 nm and c=0.4874 nm [25].

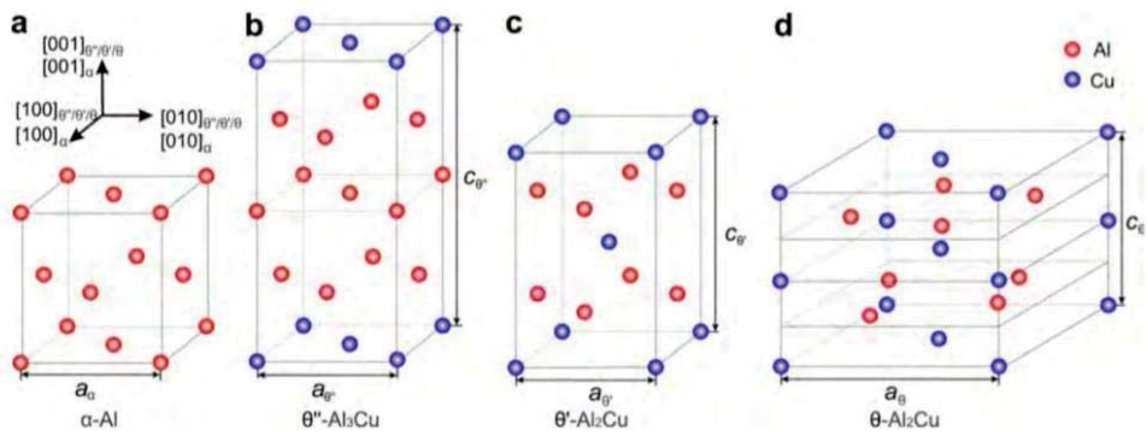

Fig. 3. Crystal structure of different precipitates [26]

The fig. 4 shows the graph of logarithm of ageing time versus strength of material which shows the strength of the sample after formation of different precipitates. As shown figure there is a peak hardness at one stage after this peak the hardness of samples decrease constantly and this is occur due to over ageing [27]. but experiments revealed that it has definite but different crystal structure than the matrix. Θ” is coherent type precipitates. This precipitates are in plate form of minimum thickness 100 A° and up to maximum diameter of 1500 A°.This precipitates has tetragonal structure. Formation of this precipitates always lead to soften the alloy.This precipitates are fully incoherent precipitates. This precipitates has tetragonal structure. Formation of this precipitates always lead to soften the alloy

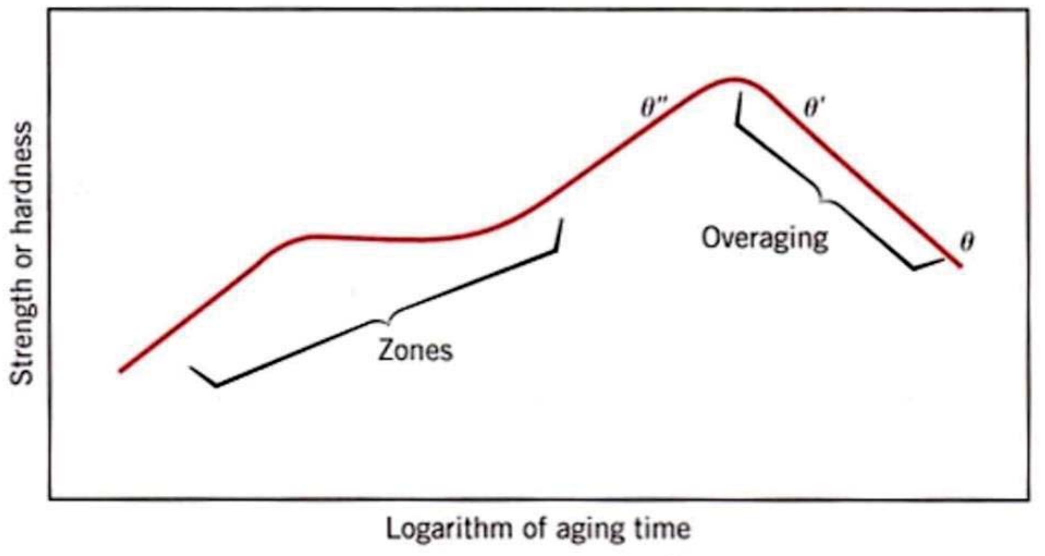

Fig. 4. Graph of strength of different precipitates [27]

1.5. Microstructure:

Fig. 5 shows the Microstructure of base metal 2024. This microstructure consist of alpha (α) and theta (θ) phase. Fig.6 shows the microstructure of annealed aluminium 2024 with different reagent like Keller's etch and week's etch. Coarse Aluminum alloy grains (~300 µm) can be observed after the solution treatment followed by quenching in water at room temperature (Fig. 7). Appearance of black spots aligned along the grain boundaries is supposed to be undissolved second phase precipitates, as also reported in [28]. Fig.8 shows the microstructure of age hardened Al 2024 which has fine alpha precipitates. This precipitates are hard in nature. These precipitates increase mechanical properties of the alloy. Smaller grains have greater ratios of surface area to volume, which means a greater ratio of grain boundary to dislocations. The more grain boundaries that exist, the higher is the strength [29].

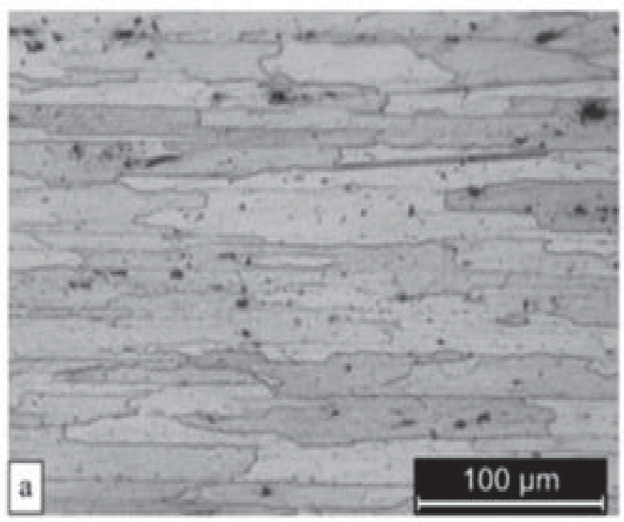

Fig. 5. Microstructure of base metal 2024 [30]

This precipitates are hard in nature. These precipitates increase mechanical properties of the alloy. Smaller grains have greater ratios of surface area to volume, which means a greater ratio of grain boundary to dislocations. Coarse Aluminum alloy grains (~300 µm) can be observed after the solution treatment followed by quenching in water at room temperature (Fig. 7). To eliminate all the residual effects that plate was subjected to the annealing process. The plate was placed in furnace at 413°C and soaked at this temperature for two hours. After this the sample was left in the furnace to cool down slowly until they had reached (250 °C) and then cooled on to room temperature.

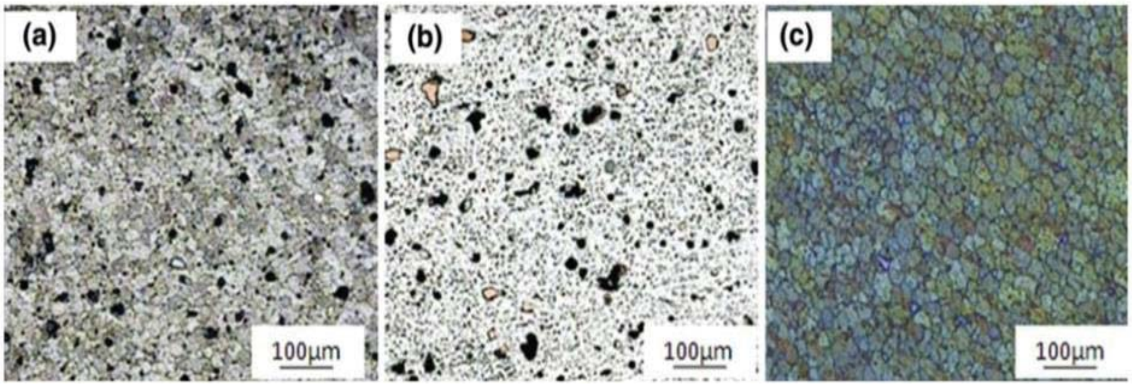

Fig. 6. Microstructures of Al 2024 – O with different reagent a Keller's etch b week's etch c new technique [31]

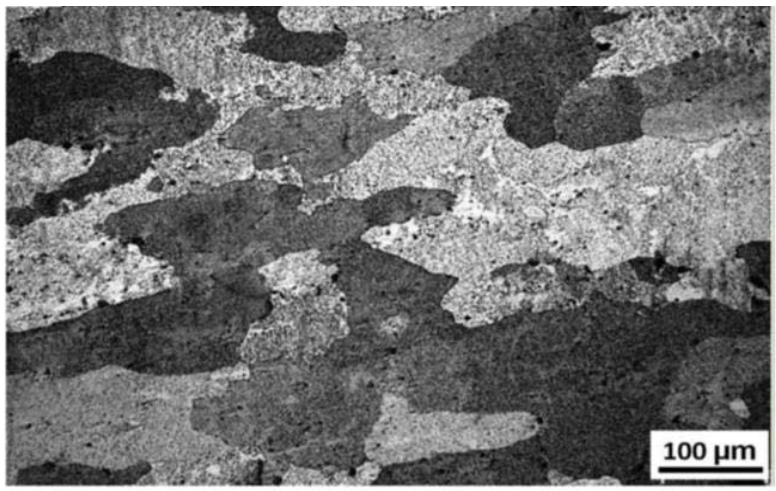

Fig. 7. Microstructures of solution treated Al 2024 [32]

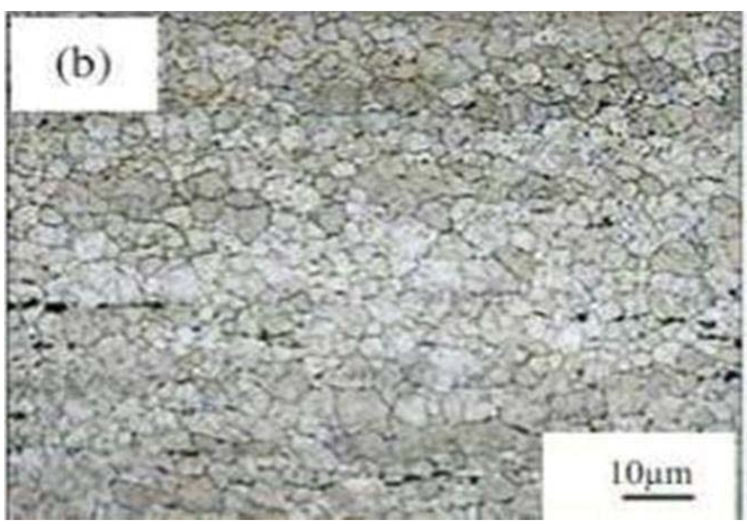

Fig. 8. Microstructure of Aluminium 2024 T6 [33]

Hussein et al [34] studied the effect of annealing, natural aging and artificial aging on properties of 2024 aluminum alloy. The study used O – Annealed, T4 – Solution heat treated and naturally aged T6 – Solution heat treated and artificially-aged alloys and the properties with water and polymeric solutions quenching medium were also studied.

Table 1. Chemical composition of 2024 [35]

Element	Al	Cu	Mg	Si	Zn	Cr	Fe	Mn	Ti	Other
% composition	90.7-94.7	3.8-4.9	1.2-1.8	0.5 max	0.25 max	0.1 max	0.5 max	0.3-0.9	0.15 max	0.05 max

To eliminate all the residual effects that plate was subjected to the annealing process. The plate was placed in furnace at 413°C and soaked at this temperature for two hours. After this the sample was left in the furnace to cool down slowly until they had reached (250 °C) and then cooled on to room temperature. Solution heat treatment was carried by performing the series of heating and cooling cycle to obtain the desired mechanical properties. This process consisted of following steps.

1. Heating to a specific temperature
2. Soaked for specific time
3. Rapid quenching in water bath
4. Age hardening

After annealing process, AA 2024-T0 was heated in the furnace up to (494°C) for about 35 minutes. At the end of this time the sample was rapidly quenched in water and returned to the furnace and heated up to (100 °C) for a period of 3 to 4 hour and cooled in room temperature. After this the specimen were cut for tensile strength and other mechanical test [34]. The mechanical and vibrational properties of AA 2024 was checked for O, T4 and T6 (annealed, naturally- aged and artificially-aged). The mechanical properties reported were as follows. The hardness of aluminium AA 2024 was measured in HRB scale at 100 kg load. The alloy obtained hardness of 101, 115, and 109 HRB for T0, T4 and T6 conditions respectively. At the same time yield strength of 150, 310, and 170 MPa, tensile strength of 340, 450 and 380 MPa, elastic modulus of 71.5, 73 and 72 GPa while % elongation of 16, 13 and 10 was obtained for T0, T4 and T6 conditions respectively [34].

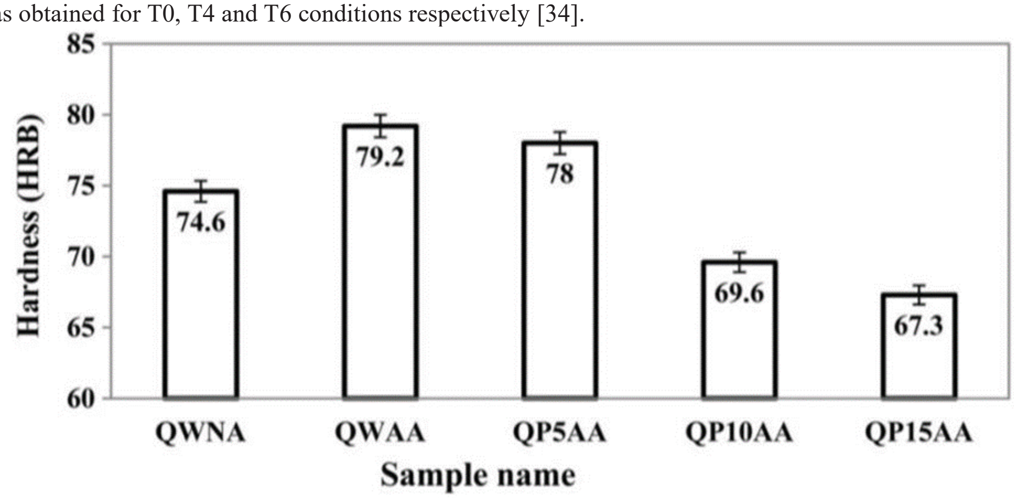

Fig. 9. Hardness of aluminum 2024 at different quenching medium [36]

The quenching medium play significant role during heat treatment. Different quenching medium can be used to get desired properties. Araghchi et. al [2] studied the effect of water quenching with natural and artificial aging and effect of different amount of polymeric solution quenching with artificial aging. Fig. 9 shows the hardness change by using different quenching mediums. QWNA is Quenching in water and natural aging, QWNA is quenching in water and mainly artificial aging, QP5AA is Quenching in 5% polymeric solution and artificial aging, QP10AA is quenching in 10% polymeric solution and artificial aging and QP15AA is quenching in 15 % polymeric solution and artificial aging. It was observed that as the percentage polymeric solution was increased, the hardness obtained decreased.

2. Summary:

From the above literature review, the effect of heat treatment like (O, T4, T6) on mechanical properties (Hardness, Yield strength, ultimate strength, modulus of elasticity and elongation) for plate 2024 can be summarized as follows:
The sample heat treated with T4 for Aluminum 2024 obtained better properties.
The mechanical properties of aluminium 2024 decreased on heat treatment with T6 condition.
Quenching medium played important role and water quenching resulted in higher hardness then polymeric solution.

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