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AES02

Investigation into Mechanical Properties of 2024-T3 Aircraft Grade Alloy after the Precipitation Hardening using Heat Treatment

M. Zulfazli R. Khan[1], M. Suffian B. A. Latib[*2], Shazana Bt. Mustapa[3]

[123]Department of Aircraft Maintenance, Politeknik Banting Selangor
Corresponding author: [2]suffian.latib@polibanting.edu.my

ABSTRACT

The purpose of this research is to investigate the behaviour of mechanical properties changes such as Rockwell hardness number of aircraft grade alloy namely 2024-T3 after undergone their specific heat treatment procedures. This mechanical impact testing will be carried out using a Rockwell hardness testing machine and complied to BS EN ISO 6508-1:1999, Metallic Materials: Rockwell Hardness Test (A, B, C, D, E, F, G, H, K) & Rockwell Superficial Test (Scale N & T). The experimental procedures regarding heat treatment process and precipitation hardening or artificial ageing on aircraft grade alloy was conducted before the specimens were tested for Rockwell Superficial Test on mechanical impact testing machine. The heat treatment process involved were solution heat treatment (SHT), quenching and followed by artificial age or precipitation hardening. The finding from this experiment revealed that a maximum hardness number of 58 HR30TS for 2024 grade alloy that is precipitated at 260°C can be achieved in 30 minutes as compared to a precipitation at a lower ageing temperature of 220°C in which reached its maximum hardness number of 65 HR30TS in a longer period of time, 120 minutes. In conclusion, it can be interpreted that a precipitation at a higher temperature will possess its maximum hardness in a shorter period of time. On the other hand, an increased temperature of precipitation will sacrifice the maximum achievable hardness number due to the behaviour of precipitation that coarsen in the matrix structure.

Key words: Solution Heat Treatment, Precipitation Hardening, Artificial Ageing, Rockwell Hardness Number

1.0 INTRODUCTION

As the introductory level, heat treatment plays an important role in aviation industry especially solution heat treatment and precipitation hardening prior its use such as a batch of rivets to be installed into airframe skin. This treatment is implemented into aircraft grade alloy such as 2017, 2117, 2024, 6061 and 7075 aluminum alloy accordingly to the specific temperature and ageing time. As a result of this importance, a feasibility study towards the changes of the mechanical properties on aircraft grade alloy after the heat treatment will help to develop a better conceptual on the effect of heat treatment on the chosen aluminum alloy such as 2024-T3 grade alloy.

1.1 Research Objectives

The main objective of this experiment is to investigate on the effect of heat treatment on aircraft grade alloy in terms of its mechanical properties such as its hardness number. Therefore, the interest of the study includes:

i. Set up the preparation of test samples that follow the British Standard for Superficial Hardness Testing specimen requirements.

ii. Conduct a laboratory procedure of solution heat treatment, age hardening and subsequently carrying out the hardness testing on the test samples.

iii. Compare and discuss the mechanical properties of the chosen aircraft grade alloy using Rockwell Hardness Number after the completion of the heat treatment procedures.

1.2 Initial Expectations of the Experiment

Throughout this research, there are a series of experiments that will be conducted on aluminum alloy 2024 that includes solution heat treatment, quenching, and artificially aged. In terms of precipitation hardening of aluminum alloy, a prolonged ageing time at a lower temperature will reserved a higher mechanical strength such as hardness properties in comparison to a reduced ageing time at a higher artificial ageing temperature.

2.0 RESEARCH BACKGOUND

2.1 Heat treatable Wrought Alloys

These are the precipitation hardening alloys. Many of these alloys are based on a 3% to 4% copper content, but lithium or magnesium and silicon can also be used to trigger precipitation. The copper is fully dissolved above a given solution temperature, but then attempts to precipitate a copper/aluminum compound ($CuAl_2$) when the alloy is cooled. This stiffens the structure of the alloy, making it hard, strong and tough. A typical heat treatable aluminum alloy used for highly stressed aircraft structures would for example, contain copper (4.3%), silicon (0.7%), magnesium (0.5%) and manganese (0.7%). Other aluminum alloys in this group are based on copper, magnesium and zinc. The alloys that are generally used in structural repair are 2017, 2117, 2024, 6061 and 7075.

Table 1 : American Coding System for Wrought Aluminum Alloy

Series	Major Alloying element
1XXX	Pure aluminum
2XXX	Copper
3XXX	Manganese
4XXX	Silicon
5XXX	Magnesium
6XXX	Silicon/magnesium
7XXX	Zinc
8XXX	Other Elements

This is a four-digit code issued by Aluminum Association. The first digit identifies the major alloying element. The second digit identifies any modifications that have been made to the impurity limits. The final two digits in the 1XXX series give the aluminum content in hundredths of one percent that exists above the 99% purity content. When series other than 1XXX are used, the last two digits identify the different alloying elements in the series. The code is printed on approximately every square foot of sheet metal[1].

2.2 Heat Treatment & Precipitation Hardening of Aluminum Alloy

The heat treatable aluminum alloys usually contain between 3% and 5% of copper (Cu). The principle of heat treatment is similar and applicable to aluminum alloy 2024, hence the phase diagram of aluminum copper alloy will be introduced to understand the principle and fundamental understanding of heat treatment and as well as precipitation hardening for both materials.

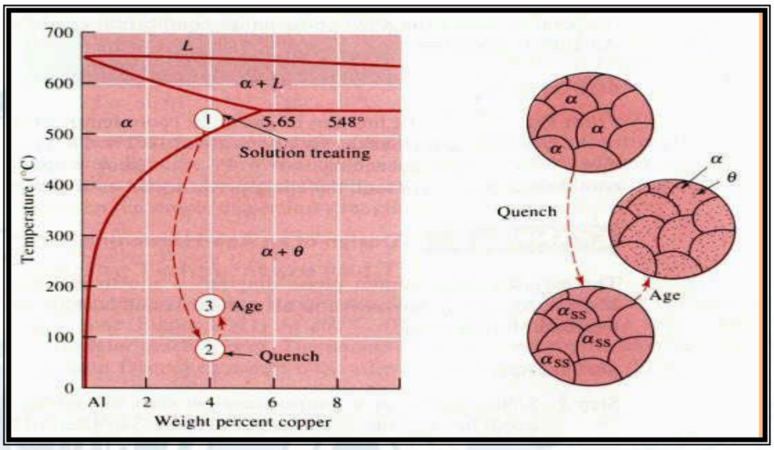

Figure 1: Aluminum Copper Alloy Equilibrium Phase Diagram2

At room temperature, aluminum will only hold 0.2% copper in a solid solution. If the aluminum is heated to above 510°C, it can dissolve a lot more copper than this into solution. According to the equilibrium diagram above, the complete heat treatment of aluminum copper alloy can be divided into three **(3)** important stages that include a solution heat treatment, followed by quenching of heat treated alloy into a cooling medium and finally artificial ageing or precipitation hardening of aluminum alloy.

For this purpose, an aluminum alloy with 4.0% copper is solution heat treated up to a temperature slightly above its solidus line for approximately 510°C. The crystal of $CuAl_2$ will gradually dissolve, until the full 4.0% amount of copper has entered a solid solution with the aluminum. Subsequently, after a solution heat treatment, the alloy will be removed from the heat and quickly quench it in water. As a result, the supersaturated copper will attempt to precipitate out but it is not easy to move around in a solid solution, so the copper will be “trapped”.

There will be no copper aluminum crystals formed in the grain boundaries, so the alloy will be strong but vey ductile. At this stage, the alloy is absolutely unstable since it has a supersaturated solid solution at room temperature and this is not in equilibrium. Over the next few hours, the excess copper will try to force itself out of solution as $CuAl_2$ and stiffening the structure of the alloy in the process. As more time passes, the alloy will become stronger, harder and less ductile.

The process can take several days and even longer, and it is known as “Age Hardening” or “Natural Ageing” that occur naturally at room temperature. Finally, the alloy will be introduced to precipitation hardening or artificial age hardening to speed up and assist precipitation of

[1] *ROSS, Robert B. (1980). Metallic Materials Specification Handbook. London: Chapman & Hall.*

[2] *ASKELAND, D. R. and Pradeep P. PHULE. (2005). The Science and Engineering of Materials. London: Thomson Learning.*

aluminum alloy to a desired hardness or required strength value. This process is a combination of two important variables, the selected precipitation temperature and a range of ageing time treatment, for example, the alloy is precipitated at 190°C for about 10 hours and then permitted to cool in air.

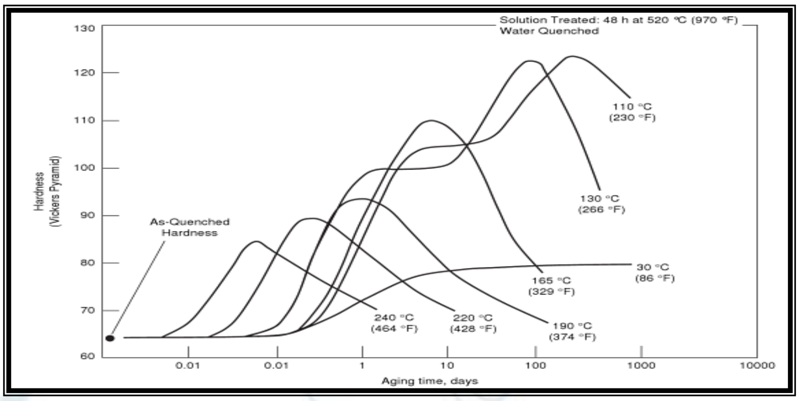

Figure 2: Ageing Curve of Al-4% Cu Alloy and Corresponding Hardness Value

2.3 Particle Strengthening & Coherency of Particles

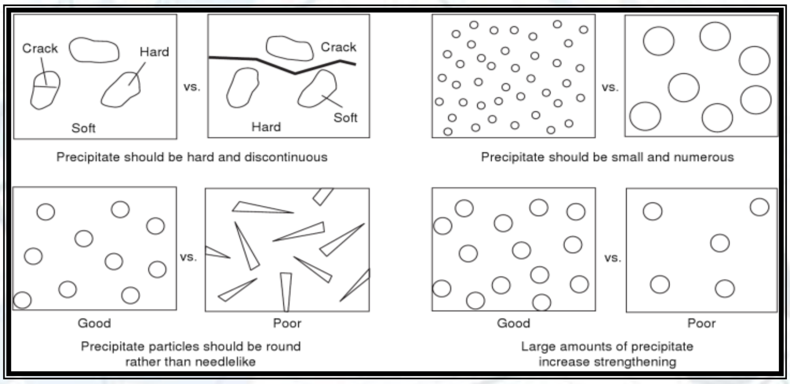

Figure 3: Conditions of Precipitate Particles for Effective Precipitation Hardening.

Particle Strengthening can be achieved in two different ways, either a precipitation hardening of the material at the elevated ageing temperature and appropriate ageing time for optimum peak strength or through a dispersion hardening which can be achieved by mechanical alloying and powder metallurgy consolidation. There are four important conditions that have to be accomplished by the precipitate particles in order to gain an optimum strength and hardness. These include the following:

i. Precipitate particles should be hard and discontinuous in comparison to the matrix that has to be soft and ductile in order to achieve a better crack propagation resistance.
ii. Precipitates have to be in a small size and numerous for an even distribution within the matrix in order to impede the dislocation movement and thus increasing the strength and hardness properties.
iii. Particles that exist in the matrix have to be in a spherical shape rather than needle like to reduce the stress concentration effects.
iv. Finally, the precipitate particles have to be in a large amount and spaced closely to one another to gain strengthening and hardening of the materials.

Furthermore, the precipitate particles that present in the matrix structure must be either coherent or even semi-coherent interface to achieve the effectiveness of precipitation hardening.

Precipitation hardening that is done to achieve a desired mechanical strength rely on the hardening mechanism in which the coherent precipitates has to be evenly distributed in the solvent matrix in order to hinder the dislocation movement and increase the slip resistance, in turn increasing the mechanical properties of the material[3].

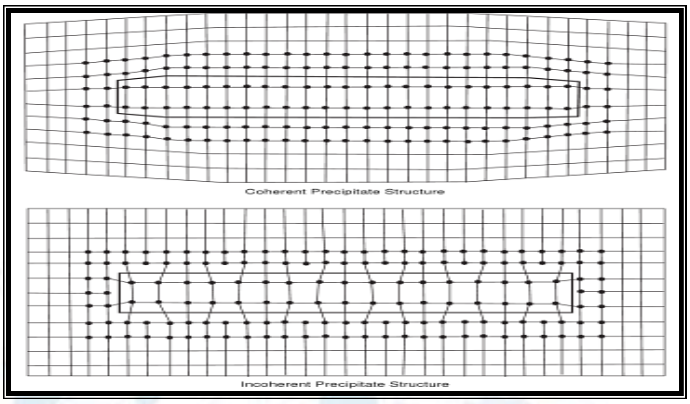

Figure 4: Formation of Coherent (top-side) & Non-coherent Particles In Matrix.

2.4 Over-Ageing and Under-Ageing Condition

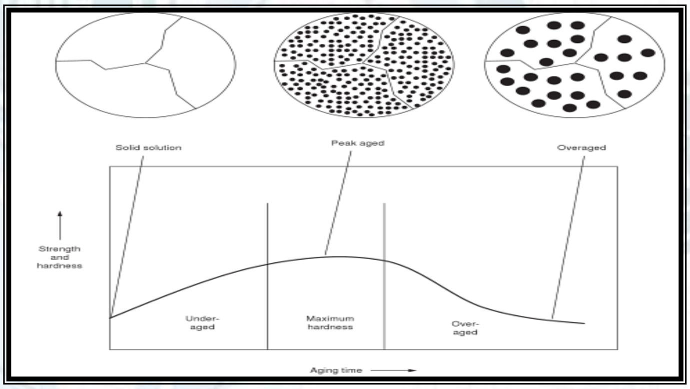

Figure 5: Typical Ageing Curve and Particle Strengthening.

When considering a precipitation hardening or artificial ageing of the aluminum alloy, a typical ageing curve is to be produced that comprises of three different areas, namely under-ageing, optimum precipitation of particles and finally over-ageing. These three terms are associated with the formation of precipitate particles due to the amount of heat introduced during the precipitation hardening. “Under-ageing” occurs at extremely low ageing temperature in which precipitates incomplete and resulting in a lower strengthening. On the other hand, if the precipitation hardening is held at extremely high ageing temperature, the precipitation particles coarsen, in which allowing an easier passage of dislocation movement thus reducing the maximum strengthening and this condition can be termed as “over-ageing”. However, optimum strength or hardness can be achieved between these two extreme ageing temperatures and this can be obtained in a reasonable ageing time.

2.5 Rockwell Superficial Hardness Test

[3] *Campbell, Flake C. (2008). Elements of Metallurgy and Engineering Alloys [Online]. Available at : http://books.google.co.uk/books?id=6VdROqeQ5M8C&lpg=PP1&dq=inauthor%3A%22Flake%20C.%20Campbell%22&pg=PP3#v=onepage&q&f=false (Accessed: 10th April 2011).*

The Rockwell Hardness test is a direct reading test that uses either a diamond cone indenter or a hardened steel ball. The Rockwell hardness test is quite convenient and time saving due to its simplicity and capacity for direct hardness value reading. One advantage of Rockwell Hardness testing over Brinell and Vickers test, it does not require any special surface preparation other than cleaning. Unlike the Brinell and Vickers tests, the Rockwell test bases its hardness value on the depth of indenter penetration and not the area of an impression

After testing sheet metal, the underside of the specimen has to be examined. If the impression of the penetrator can be visually seen, then the reading is in error and the Superficial Hardness test should be used. The Superficial Hardness test is designated for “N” and “T” scales with the selection of diamond cone indenter for “N” scales or alternatively 1.5875 mm (1/16 inch) steel ball for “T” scale. Rockwell Superficial Hardness test utilises of 3 kgf minor load, where the major loads are in the ranges of 15, 30 and 45 kgf. If the impression can still be seen after the superficial test, then a lighter load should be used. A minor load of 3 kgf and a major load of 30 kgf are recommended for most superficial testing. Superficial testing is also used for case-hardened and nitride steel having a very thin case. A Brale marked “N” is needed for superficial testing, as A and C Brales are not suitable.

3.0 METHODOLOGY

3.1 Preparation of Tensile Test Specimens

For the purpose of hardness testing procedures, the test pieces produced are referred to a current British Standard for Superficial Hardness Testing, BS EN ISO 6508-1:1999, Metallic Materials : Rockwell Hardness Test (A, B, C, D, E, F, G, H, K) & Rockwell Superficial Test (Scale N & T). A set of 15 hardness test samples for each material is produced in such a way that any alteration of the hardness test specimen surface due to heat or cold-working is minimised to ensure that this does not bring an effect to the Rockwell hardness readings. Furthermore, according to the British Standard of Rockwell Hardness Test, the thickness of the test piece shall be at least ten times the permanent indentation depth for diamond cone penetrator whereas fifteen times the permanent indentation depth for steel ball indenters.

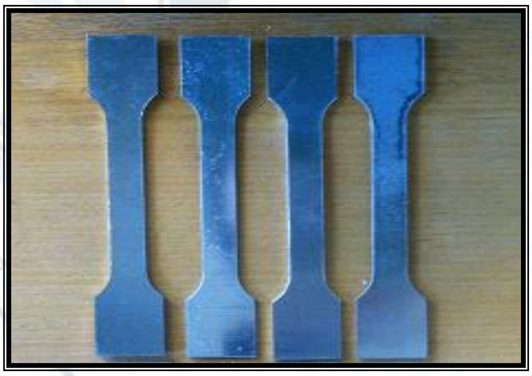

Figure 6 : Final Dimension of Hardness Test Specimen.

Table 3: Dimension for Hardness Test Pieces.

Dimension	Value (mm)
Total length ***(L$_t$)***	164.05
Thickness ***(t)***	1.27

Parallel length ***(L_c)***	75.00
Parallel Width ***(b_o)***	12.50
End Width ***(be)***	25.00

3.2 Laboratory Procedures for Heat Treatment

Heat treatment procedures will be carried out specifically with reference of data sheet material that being produced by the manufacturer and also American Society for Metal Handbook - Volume 4: Heat Treating. However, there are some alterations made to the laboratory procedures especially artificial ageing temperature and associated ageing time treatment for both aluminum alloys in order to make the objectives of the experiment possible. This experiment will be conducted using Wild Barfield Air Furnace (Model MI 354) that is capable to reach the maximum operating temperature of 1200°C. All the measurements and technical specification for using apparatus and equipments are taken into account. Heat treatment procedures include:

a) Solution Heat Treatment.
b) Quenching into a cooling medium.
c) Artificial Age Hardening.

For this case, each hardness test specimen that undergoes heat treatment process will be marked according to their specific precipitation hardening temperature and a set of ageing time for2024 aluminum alloy test pieces.

3.3 Solution Heat Treatment Procedures

1. The furnace is heated up to a temperature of (495 ºC) and left for 45-55 minutes for the temperature inside the furnace to stabilise. It is important to ensure the temperature does not fluctuate more than 10ºC. A digital thermometer is used as an alternative to assure the temperature inside the furnace is matched to the SET POINT temperature.[4]

2. The furnace door is opened and the test pieces were inserted into the furnace using a thong after a temperature has settled at desired value. The specimens were placed next to each other and spaced equally to enable even heat distribution. The furnace door was then closed immediately in order to minimise the risk of heat escaping from the furnace that possibly affect the correct temperature of heat treatment.

3. After all the specimens were inserted inside the furnace, a digital stopwatch is started as soon as the temperature reaches 495ºC again. The specimens are solution heat treated at 495°C and soaked for 45 – 60 minutes.

3.4 Quenching of Heat Treated Specimens

1. A metal bucket is filled up with a sufficient amount of water with a temperature between 70-80ºC which can be measured using a digital thermometer.

2. After 45 minutes of solution heat treatment has lapsed, the specimens were immediately removed from the furnace and instantly quenched into the water. The maximum time delay allowed for quenching process is no more than 10 seconds. Safety precaution has to

[4] *AMERICAN SOCIETY FOR METALS. (1991). ASM Metals Handbook Volume 4 : Heat Treating. Ohio: ASM International.*

be taken into account especially when removing hot specimen from the furnace and hot vapour from the water during quenching.

3. The temperature in the water is monitored using a digital thermometer. During the quench, the heat treated specimens were agitated to ensure an even transfer of heat into the cooling medium.

4. All the specimens were totally immersed in the water for several minutes to ensure the specimens are cooled down to a room temperature.

3.5 Artificial Ageing Procedures for 2024 Aluminum Alloy

1. Following a quenching process, the furnace is heated up to a temperature of 260°C and the furnace is left for 45-55 minutes for the temperature to stabilise.

2. After 45-55 minutes has lapsed and the temperature inside the furnace stabilised, the marked specimens were inserted into the furnace.

3. A digital stopwatch will be started as soon as the furnace door is closed and the temperature is stabilised once again at 260°C.

4. The specimens are artificially aged at 260°C with an ageing time intervals of 5 minutes, 30 minutes, 60 minutes and 240 minutes. The specimens are spaced equally for an even heat distribution and grouped accordingly to its ageing time treatment.

5. The first sample is removed from the furnace after 5 minutes of precipitation heat treatment and left to cool down at ambient temperature. Opening and closing of the furnace door was carefully controlled to ensure the remaining specimens are precipitated at a correct temperature.

6. Subsequently, next samples are removed from the furnace according to their respective ageing time and this step is repeated until all the specimens are completely precipitated at their specific time.

7. Step 1-6 is repeated for a precipitation hardening at 220°C with different time intervals that includes 5 minutes, 30 minutes, 120 minutes and 240 minutes.

Table 4: Heat Treatment Procedures for 2024 Materials.

Material	Solution Heat Treatment	Soak Time	Quench	Artificial Ageing Temperature	Ageing Time (minutes)
2024 Aluminum Alloy	495°C	45-60 minutes	70°C - 80°C (less 10 sec) Delay time.	260°C	5
					30
					60
					240
				220°C	5
					30
					120
					240

Following a series of artificial ageing treatment, all the specimens are then carried out for a mechanical testing to investigate the mechanical properties changes such as its hardness number due to a previous heat treatment. A Rockwell Superficial hardness testing is more preferable in comparison to a Rockwell Normal hardness testing due to a type of material used for the specimen that is aluminum alloy and the thickness of the specimen; 1.27 mm or 0.050 inch that is considerably as a thin test piece. For this purpose, a Rockwell Superficial hardness testing is conducted in accordance to a BS EN ISO 6508-1:1999, Metallic Materials: Rockwell Hardness Test (A, B, C, D, E, F, G, H, K) & Rockwell Superficial Test (Scale N & T).

Table 5: Summary of Weights and Indenters used for Rockwell Superficial Test.

Materials	Treatment of Specimens	Types of Penetrator	Rockwell Superficial Scale	Total Loads
2024	Artificially Aged	Steel Ball (1/16 inch) Diameter	30T	30 kgf

4.0 RESULTS & DISCUSSION

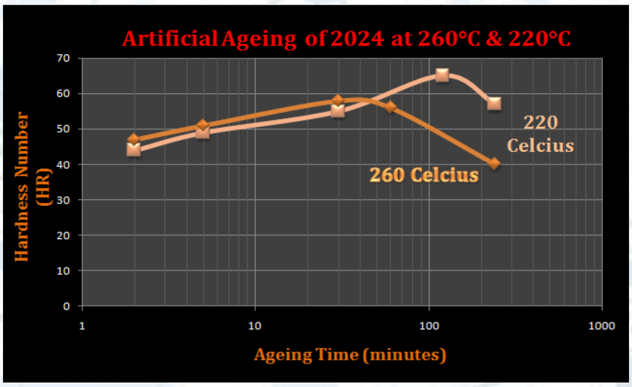

Figure 7 : Artificial Ageing for 2024 Aluminum Alloy at 260°C & 220°C.

Table 6 : Table of Artificial Ageing Treatment & Maximum Hardness Value for 2024

Material	**Artificial Ageing Temperature**	**Artificial Ageing Time**	**Maximum Hardness Number**	**Superficial Hardness Scales**
2024	260°C	30 min	58 HR30TS	30T / 30 kgf (1/16 inc) Diameter Steel Ball
	220°C	120 min	65 HR30TS	

In conclusion, it can be interpreted that a precipitation at a higher temperature will possess its maximum hardness in a shorter period of time. For an example, a maximum hardness number of 2024 that is precipitated at 260°C can be achieved in 30 minutes with the hardness number of 58 HR30TS as compared to a precipitation at a lower ageing temperature of 220°C in which reach its maximum hardness number of 65 HR30TS in a longer period of time, 120 minutes, three time longer than the previous one.

It is important to relate this phenomenon to a precipitation of the particles within the matrix. It is understandable that a lower ageing temperature will exhibit a higher value of hardness due to the formation of finely dispersed particles during precipitation. These fine particles that precipitates into the matrix are small in size, numerous, distributed evenly within the matrix structure and coherent to the matrix. The term “coherent” makes the particles arranged themselves in a crystal structure that has a strong and definite relationship between the precipitate’s and matrix’s crystal structure. As a result, all these properties make the precipitates to act as a barrier in order to impede the dislocation movement within the lattice, in turn increase the maximum attainable strength and hardness.

On the other hand, an increased temperature of precipitation will sacrifice the maximum achievable hardness number due to the pecipitates behaviour that coarsen in the matrix structure. This tends to form the particles that are of greater size and widely spaced that allow easier passage of dislocation and sacrifice the hardness of the material. Furthermore,a precipitation at a high temperature, for example an alloy that aged for 20 minutes at 260°C, exhibit the properties that are non-uniform due to the surface of the alloy that is properly aged whereas the centre of the alloy remains cool and aged slightly.

5.0 CONCLUSION AND RECOMMENDATIONS

Throughout a series of experiment conducted in this research, it can be concluded that the aim and objectives of the research outlined at the beginning of the work are successfully accomplished. The aim of the experiment to investigate the mechanical properties changes through precipitation hardening of aircraft grade aluminum alloy such as 2024 materials have been fully understood and implemented within the scopes of the objectives of the research. Furthermore, heat treatment laboratory procedures that comprises of solution heat treatment, rapid quenching and artificial ageing of the specimens has been fully covered.

5.1 Limitations of the Research

Throughout the experiments, there are some limitations that contribute to affect the accuracy and consistency of the aim and objectives of the research.

- **Acquisition of the material**

The acquisition of material, 2024 aluminum alloy from the Barry College was not in a satisfactorily condition as some parts of the surface are adversely scratched and even worst, a deep indentation can be found on the surface and this in turn will affect the accuracy of the test result since the Rockwell hardness testing is very sensitive on the smooth surface of the material.

- **Facilities and Equipments**

The furnace is not 100% reliable since the capability of the furnace to regulate and control a correct temperature during heat treatment is not in a satisfactorily condition. This may affect the correct procedure of solution heat treating and artificially aged the specimen at the correct temperature over a period of time.

- **Manufacturing of the test samples**

Methods of manufacturing the test sample must be taken into account as not to bring an affect towards its mechanical properties after the manufacture work is done. This is because a Rockwell superficial hardness testing relies on the hardness surface of the specimen, and any dent or scratch will greatly affect the depth of the penetration of the indenter, and this in turn will adversely affect the accuracy of the hardness number of the specimen.

5.2 Improvements & Recommendations for Future Research

- Heat treatment and investigation into precipitation hardening on different types of materials, for an example ferrous materials or different series of aluminum alloy such as 6000 series.
- A study of new developed and commercial materials, such as GLARE and other Fibre Metal Laminates (FML) composite materials in comparison to a metallic material such as aluminum alloy and its series.
- Develop other types of mechanical testing on the specimen such as tensile testing or other hardness testing that include Brinell and Vickers Hardness test to greatly increase the capacity of test results for accurate comparison

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