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# Effect of Vegetable Oil Quenchants and Precipitation Hardening on the Mechanical Properties of Aluminum Alloy (AA2024)

**Hawre F. Amin**[*,1], **Abbas I. Khwakaram**[1], **Omer S. Mahmood**[2], **Pshtiwan M. Karim**[1], **Rekawt R. Amin**[1]

[1] Sulaimani Technical Institute, Sulaimani Polytechnic University, Sulaimani, Iraq.
[2] Mechanical and Manufacturing Engineering, Sulaimani Polytechnic University, Sulaimani, Iraq.

## ABSTRACT

This article demonstrates how different cooling rates and precipitation hardening affected the mechanical properties of AA2024. Three impact test samples were chosen. Solution heat treatment was conducted at 500 °C for 2 hrs., followed by quenching in three different quenching media (Sunflower Oil, Sesame Oil, and Corn Oil). As a result, the Sunflower Oil showed the lowest shock absorption rate; hence, it was chosen as the quenching medium for this study. Consequently, all samples of tensile, hardness, and impact tests were solution heat treated at 500 °C for 2 hours, then quenched in Sunflower Oil to room temperature and artificially aged at temperatures of 180°C for 1,2,4 hour, 195°C for 1, 2, 4 hour, and 210°C for 1,2,4 hour. Considerable improvements in strength and hardness were observed while decreasing the ductility Due to the production of finely dispersed grains. Precipitation hardening at 180°C for 1 hour was the overall optimum achievement, which enhanced the UTS by 28.7% to 579 MPa, compared to the as-received sample with UTS 450 MPa. While annealing has reduced the UTS by 32.7% to 303 MPa.

**Keywords:** Aluminum alloy 2024, Heat treatment, Precipitation hardening, Quenching, Sunflower oil.

## 1. INTRODUCTION

Aluminum is among the most significant Engineering materials because of its superior properties like heat and electrical conductivity, lightweight, corrosion resistance, and ease of fabrication **(Zain Al-Abideen et al., 2017; Siqueira et al., 2019; Akande et al., 2022; Garchani et al., 2023**). Many factors affect the mechanical properties of aluminium alloys,

*Corresponding author
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including the alloy composition, manufacturing method, solidification rate, existence of iron intermetallic (Mg + Cu), and Si content; for instance, AA2024 inherits its mechanical properties from the precipitation of hardening S–Al2CuMg phase obtained through appropriate heat treatment **(Zheng et al., 2015; Beroual et al., 2019; Esin et al., 2021).** Each alloy affects the aluminium property differently. Some elements, such as zinc, lithium, or copper, increase some mechanical properties. However, these alloying components increase the alloy's susceptibility to localized corrosion due to producing a heterogeneous microstructure **(Saillard et al., 2018).** On the other hand, some other alloys enhance the corrosion resistance while showing medium strength, such as (Al–Mg–Si) alloys as well as Sr alloy, which hinders the growth of copper-rich second phase particles in the Aluminium Alloy 2024 which lead to the elemental copper content increase as a result improves the corrosion resistance of the Aluminium alloy, and these alloys are widely used in automotive body panels and extruded products **(Ozturk et al., 2010; Li et al., 2016; Sun et al., 2023).**
Aluminium Alloy 2024 is a common 2xxx Al–Cu–Mg series Al alloy. As a competitive lightweight material with high yield strength and fatigue resistance, AA2024 has been widely used. An energy conservation and emission reduction rate can be achieved by using lightweight alloys like Aluminium Alloy **(Moy et al., 2012; AL-Alkawi et al., 2015; Westermann et al., 2016; Sun et al., 2021; Shen et al., 2023).**
In the field of automotive and aerospace, there is always a vast demand for materials with lightweight and high strength ratio properties to obtain the best component structure and fuel economy. Hence, scientists and researchers in the field always seek to improve the mechanical properties of this metal to a higher level. Aluminum's mechanical strength and casting properties can be enhanced by adding alloying elements such as manganese, copper, nickel, zinc, silicon, and magnesium. The addition of copper to Al–Si alloys cause the formation $CuAl_2$ phases, which results in increasing strength of the casting part. Meanwhile, copper increases the heat treatability of the alloy **(Shabestari and Moemeni, 2004; AL-Alkawi et al., 2015; Kayani et al., 2023).**
Heat treatment is another choice to improve the mechanical properties of Aluminum Alloys, which are heat treatable. Precipitation hardening and ageing, specifically artificial ageing, are common methods employed **(Radutoiu et al., 2012; Jang et al., 2013; AL-Qaisy et al. 2017; Akande et al., 2022).** A study by **(Sadeler et al., 2004)** showed that "the fatigue strength at $10^7$ cycles of Al alloy was improved by approximately 43%, compared with cast alloy by ageing after solution treating temperature of 510°C". The corrosion resistance of aluminium alloy, a vast consideration to the designers and manufacturers, especially in the automotive and aerospace industries, can also be improved by heat treatment of the aluminium alloy. Researchers mentioned that the over-ageing treatment should stabilize the microstructure of aluminium alloy and improve the corrosion resistance **(Radutoiu et al., 2013; Siskou et al., 2018; Garchani et al., 2023)**.
Researchers stated that artificial ageing could enhance corrosion resistance, and it generally depends on the ageing time of the process. **(Onat, 2018)** mentioned in his research that the corrosion rate decreases with ageing time and obtained the optimum artificial ageing time of 10 hrs. corresponding with the lowest corrosion value of 0.0123 mm/year.
**(Kumar et al., 2022)** mentioned that the 2xxx, 6xxx, and 7xxx series of Aluminium Alloy are heat-treatable alloys. The Aluminium 2xxx series contains Cu at a range of (2.5–5.0%) and other alloying elements are generally artificially aged, and solution heat-treated. Since Al alloy 2024 belongs to Aluminium 2xxx series, its microstructure can be modified due to subsequent heat treatment processes to enhance the mechanical properties.

The most frequent method of heat treatments for Al alloys is Solution treatment and ageing **(Staszczyk et al., 2019; Liang et al., 2020).** The rapid quenching results in the formation of the supersaturated solid solution. Then, during natural or artificial ageing, various enormously strong phases precipitate. Researchers in this field have become interested in this because the parameters of both the ageing and solution treatments have a significant impact on the improvement of the final mechanical properties of the Al alloys **(Sjölander and Seifeddine, 2010; Araghchi et al., 2018; Liang et al., 2020).**
Solution treatment with subsequent natural or artificial ageing is the most common heat treatment of Al Alloy 2024. This led to a tremendous improvement in the mechanical properties of Al alloy 2024 with the scientific control of the solution and ageing parameters. Considerable improvements in the mechanical properties of cold-rolled Al Alloy 2024 can be achieved by controlling the solution and ageing parameters in a scientific manner **(Gurugubelli, 2012; Smeadă et al., 2012; Singh et al., 2016; Sun et al., 2021).** The precipitation hardening severely affects the mechanical properties of the Al Alloy 2024. As mentioned, in the aircraft industry the Al alloy 2024 is widely used. Therefore, studying how artificial ageing affects Al alloy 2024's mechanical properties is essential, particularly when it comes to properties like tensile stress and ductility, which are frequently linked to fracture toughness that is taken into account during the design stage of aircraft structures **(Alexopoulos et al., 2017; Österreicher et al., 2023).**
Aluminum alloys undergo precipitation hardening, which is the process of dissolving solute atoms in the aluminum lattice at high temperatures, retaining the resulting solid solution by quenching, and then ageing the alloy. During this process, solute atoms diffuse through the matrix and form precipitates, which are ordered solute complexes with their lattice structure, as a result, increase the mechanical properties of the aluminum alloy, such as hardness property **(Yang and Banhart, 2021; Sun et al., 2022).** The Solution treatment and ageing parameters mainly include solution temperature and time, ageing temperature and time **(Sun et al., 2021).**
It is noteworthy to mention that the pre-deformation of the Aluminium Alloy influences the ageing process, especially ageing time. In research by **(Kolar et al., 2012),** pre-deformations strongly affect the precipitation kinetics and associated mechanical response regarding tensile and hardness properties. Based on that, the pre-deformations involve the solution treatment and artificial ageing process; annealing is done to the samples of this study.
This study mostly focuses on the ageing parameters. However, the optimum quenching medium (Sunflower oil) for Solution treatment was chosen amongst three media (Sesame Oil, Sunflower Oil and Corn Oil). It was investigated that great mechanical properties were improved; Ultimate tensile strength and Hardness values were achieved.
This work aims to reveal the influence of the Solution treatment and Ageing parameters, mainly ageing temperature and ageing time, on the mechanical properties of Al alloy 2024 and demonstrate the important role of artificial ageing in enhancing mechanical properties, particularly Hardness and Ultimate tensile strength.

## 2. Experimental work

### 2.1 Materials

This study was conducted on:
1- A 10 mm-thickness Al alloy 2024 plate.

Charpy V-notch Specimens as shown in **Fig. 1** were made in Sulaimani Technical Institute according to ASTM standards with the dimensions Width of 10 mm, thickness of 10 mm, and length of 55 mm.

**Figure 1.** Experimental work on the Al alloy 2024 to make Charpy V-notch Specimens machined by milling machine operation.

2- A 20 mm (diameter) Al alloy 2024 round bar was used to prepare tensile test specimens; the tensile test specimens shown in **Figs. 2 and 3** were made on a CNC lathe in Sulaimani Technical Institute according to ASTM E8 standard.

**Figure 2.** Experimental work on the Al alloy 2024 to make tensile test specimens machined by CNC lathe machine operation.

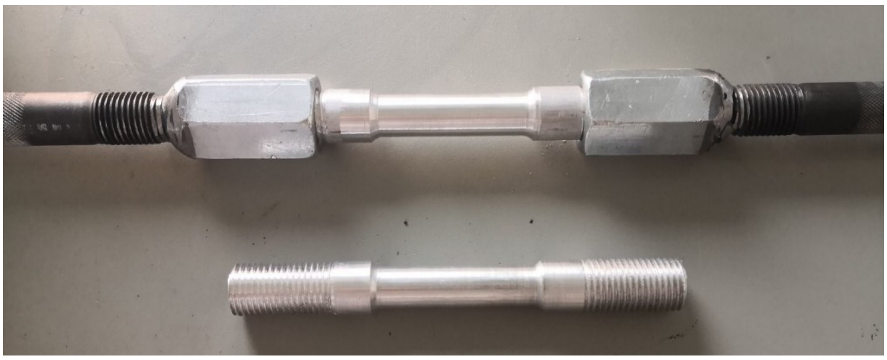

**Figure 3.** Tensile test specimens and a fixture made to fit the test specimens with the tensile test machine.

Both mentioned specimens were used for the heat treatment process in this study. **Table 1.** displays the Al Alloy 2024 Chemical Composition. The composition test was done by Iralex Company (Iraq Aluminium Extrusion).

**Table 1.** Chemical Composition of Al alloy 2024.

| Element | Si | Fe | Cu | Mn | Cr | Mg | Pb | Zn | Other | Al |
|---|---|---|---|---|---|---|---|---|---|---|
| % Composition | 0.13 | .021 | 4.40 | 0.50 | 0.01 | 1.45 | 0.01 | 0.01 | | balanced |
| Min.<br>Max. | 0.50 | 0.50 | 3.8<br>4.9 | 0.3<br>0.9 | 0.1 | 1.2<br>1.8 | 0.05 | 0.25 | 0.15 | |

To know the tensile strength values of the received material Al alloy 2024, a Tensile test was performed on the received specimens on Universal Testing Machines 1000KN in Sul Steel Company (For Steel Rebar Production) before the materials underwent heat treatment. **Table 2** displays the experimental values for ultimate tensile and yield strength.

**Table 2.** The value of mechanical properties for as-received material.

| As-received material | Experimental Value |
|---|---|
| Ultimate tensile strength | 450 MPa |
| Yield strength | 315 MPa |

## 2.2 Heat Treatment

Three impact test samples were heated at 500 °C in a Carbolite Thermolyne model box furnace shown in **Fig. 4** for 2 hours to select the optimum quenching media. The selected temperature is suitable for a solution treatment of Aluminum alloy **(Esin et al., 2021)**. Then, the samples were quenched (Sesame Oil, Sunflower Oil and Corn Oil). A Charpy Impact test was conducted on the samples, and it was found that samples quenched in Sunflower Oil produced the lowest rates of impact energy. **Fig. 5** displays the results of the specimens used for the impact test.


**Figure 4.** High-Temperature Furnace "Thermolyne model box Furnace" used for this study's heat treatment purpose.

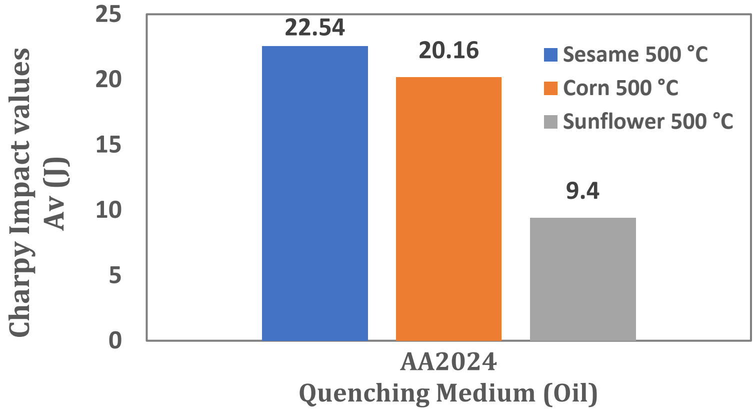


**Figure 5.** Charpy impact test for various quenching medium, solution heat treated at 500°C,2h.

After selecting the optimum quenching medium, "Sunflower Oil," all samples of the tensile and impact tests were heated in the furnace at 500 °C for 2 hours and then quenched in Sunflower Oil to room temperature, artificially aged at 180 °C for 1,2,4 hour, 195 °C for 1,2,4 hours, and 210°C for 1,2,4 hours. Meanwhile two samples from the tensile and impact tests were annealed, samples heated in the furnace to 500 °C and kept in the furnace for 24 hours to recover the samples to their normal conditions. **Fig. 6** demonstrates a schematic of the heat treatment process.

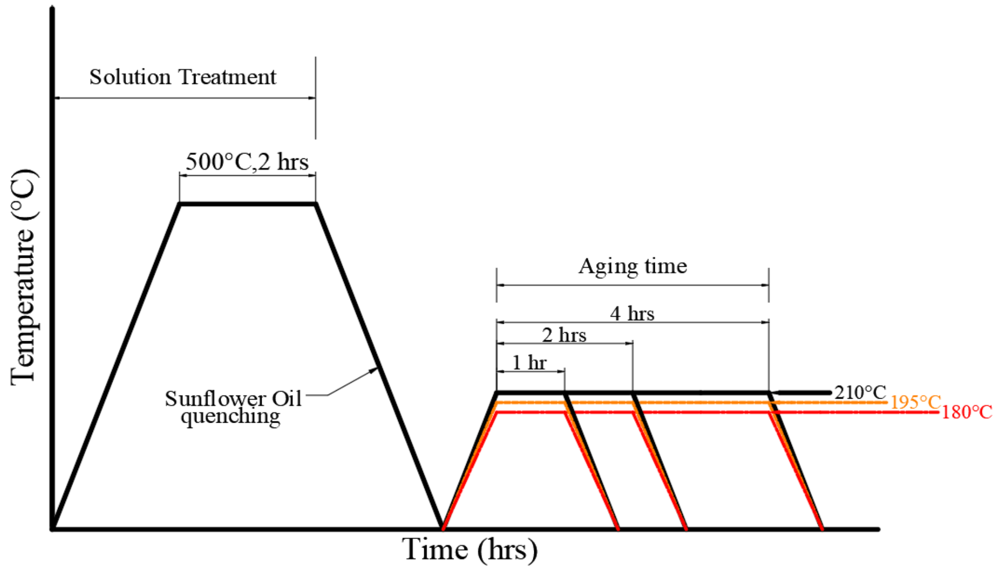


**Figure 6.** Schematic of Solution Treatment and Ageing Time on Al alloy 2024.

## 3. RESULTS AND DISCUSSION

For a quick comparison, the results of all the tests done on all the specimens for this study are shown in **Table 3** below; results of tensile tests, hardness, and impact tests will be discussed separately in detail.

**Table 3.** Hardness, ultimate tensile strength, and impact values.

| Sample No. | AA2024 Sunflower Oil | Hardness HRB | Ultimate Tensile Strength N/mm$^2$ | Charpy Impact values Av (J) |
|---|---|---|---|---|
| 1 | 180 °C / 1 hr. | 82.53 | 579.97 | 10.23 |
| 2 | 180 °C / 2 hrs. | 65.12 | 548.27 | 18.41 |
| 3 | 180 °C / 4 hrs. | 79.25 | 573.15 | 12.25 |
| 4 | 195 °C / 1 hr. | 65.95 | 548.97 | 18.25 |
| 5 | 195 °C / 2 hrs. | 79.19 | 569.47 | 11.06 |
| 6 | 195 °C / 4 hrs. | 68.31 | 564.39 | 11.26 |
| 7 | 210 °C / 1 hr. | 64.83 | 547.82 | 18.75 |
| 8 | 210 °C / 2 hrs. | 61.53 | 501.49 | 19.06 |
| 9 | 210 °C / 4 hrs. | 78.36 | 569.72 | 10.73 |
| 10 | Annealing 500°C/24 hrs | 26 | 301.20 | 19.79 |

### 3.1. Result of Tensile Test

Tensile tests were done using Universal Testing Machines 1000KN, in Sulaymaniyah Steel Co. in Iraq, on the prepared samples, which were already heat treated and aged, as mentioned in the previous section of this study. The stress and strain curve of all artificial ageing temperatures and hours are shown in **Figs. 7 to 10.**

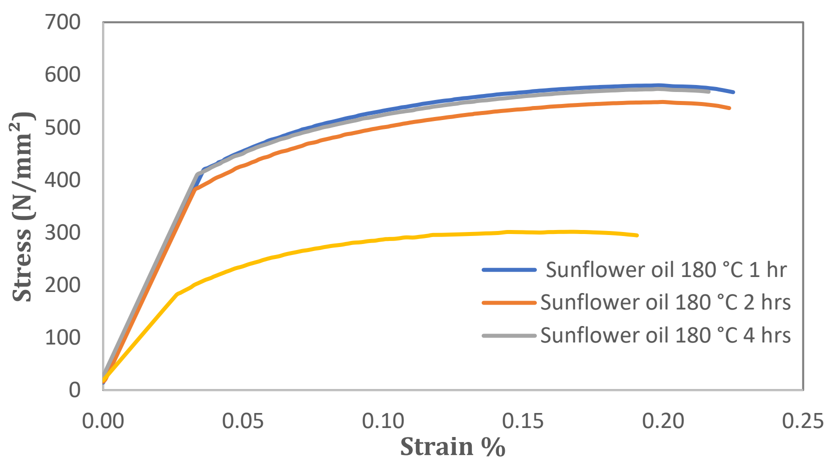


**Figure 7.** Tensile strengths vs. Strain curves for Al alloy 2024, solution heat treated in Sunflower Oil and aged at 180 °C (1,2,4) hrs.

Here, in **Fig. 7,** it can be seen that the highest ultimate Tensile strength is achieved (579.97 N/mm$^2$) at 180 °C 1 hr, which is the highest achieved tensile strength among all the tested samples. This can be considered a reasonably good achievement as it needs the lowest ageing time, which is one hour. In **Fig. 8**, it can be observed that the highest ultimate Tensile strength is achieved (569.47 N/mm$^2$) at 195 °C / 2 hrs. For this temperature, the highest tensile strength achieved (569.47 N/mm$^2$) is at 2 hours, which is a higher time "twice the time" at the same time lower tensile strength compared to the highest tensile strength at at 180 °C 1 hr. which is (579.97 N/mm$^2$).

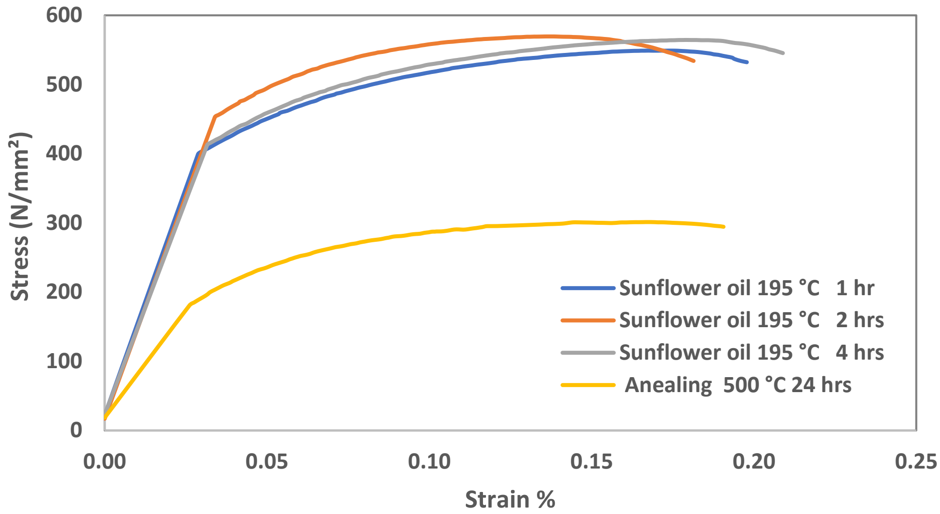


**Figure 8.** Tensile strengths vs. Strain curves for Al alloy 2024, solution heat treated in Sunflower Oil and aged at 195°C (1,2,4) hrs.

Here, in **Fig. 9**, it can be seen that the highest ultimate Tensile strength is achieved (569.72 N/mm$^2$) at 210 °C 4 hrs.

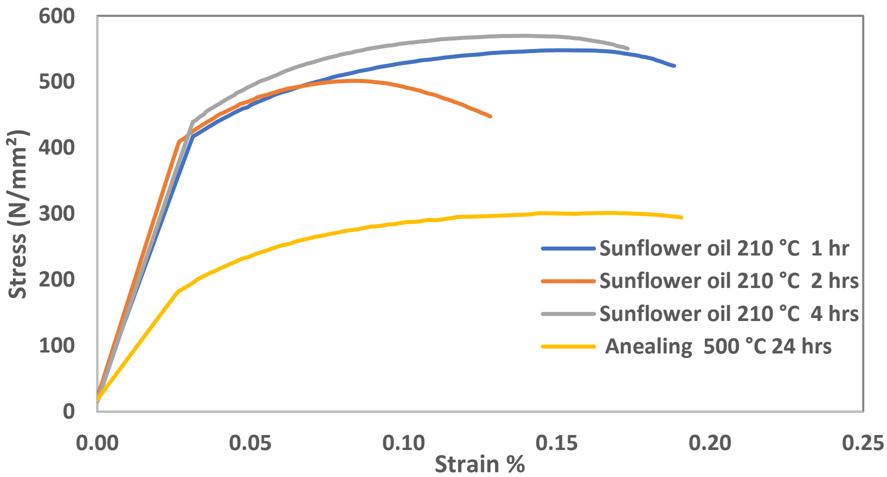


**Figure 9.** Tensile strengths vs. Strain curves for Al alloy 2024, solution heat treated in Sunflower Oil and aged at 210 °C (1,2,4) hrs.

The best result at 210 °C is at 4 hours with the value of tensile strength achieved (569.72 N/mm$^2$) compared to the best results achieved in the two mentioned temperatures 180 °C and 195 °C which are (579.97 N/mm$^2$) at 180 °C 1 hr. and (569.47 N/mm$^2$) at 195 °C / 2 hrs. Therefore, it can be said that 210 °C compared to 195 °C is more time consuming and compared to 180 °C achieved lower tensile strength and is more time-consuming. Here, in **Fig. 10**, it can be seen that the highest ultimate Tensile strength is achieved (579.97 N/mm$^2$) at 180 °C 1 hr. compared to the annealed sample (301.20 N/mm2). There is a considerable difference between the two values. The ultimate Tensile strength of the solution heat treated in Sunflower Oil at 180 °C 1 hr. is nearly twice that of the annealed sample.

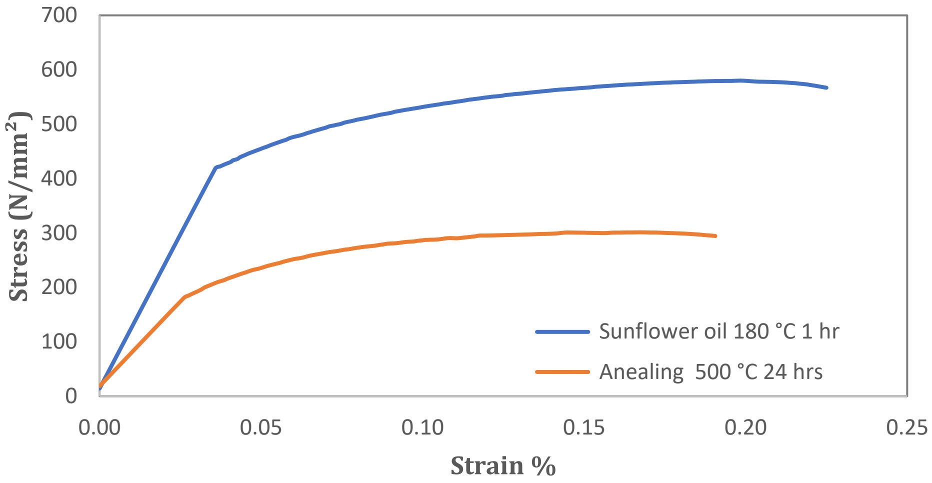


**Figure 10.** Tensile strengths vs. Strain curves for Al alloy 2024, solution heat treated in Sunflower Oil at 180 °C 1 hr. And (annealing) sample.

### 3.2. Result of Hardness Test

After the Solution treatment and artificial ageing were conducted on the Charpy V-notch samples, hardness tests were done Using Brinel Testing Machines in Mass Iron and Steel Industry Co.-Iraq. Each value listed is the average of three hardness test readings made at various positions of each sample. **Fig. 11** shows the hardness values as a function of artificial ageing time for the samples. The Maximum hardness of the Al alloy 2024 achieved is HRB 82.53, belong to the sample aged at 210°C and for 1 hr.

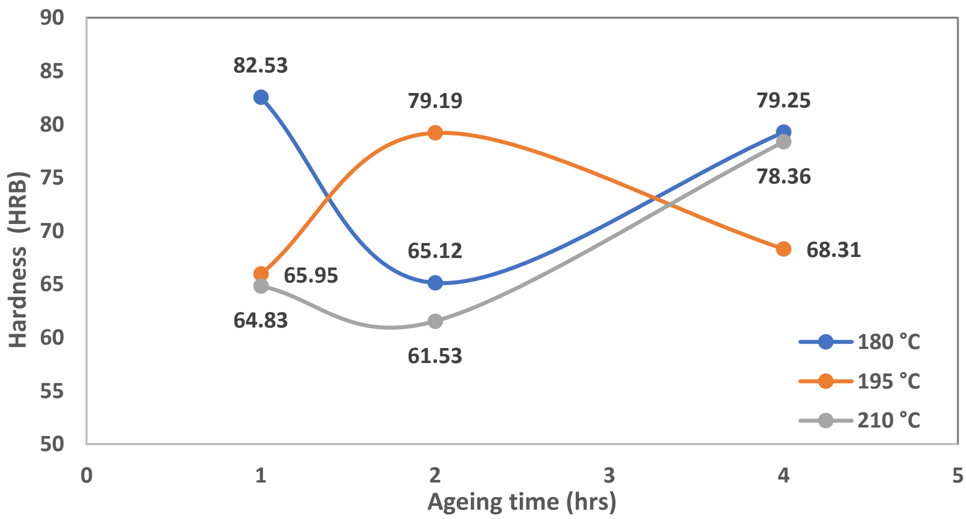


**Figure 11.** Hardness for various ageing time and temperature curves for Al alloy 2024.

### 3.3. Result of Impact Test

The Charpy Impact Test was performed on the Charpy V-notch samples using the Charpy Impact Testing Machine. In Sulaimani Polytechnic University/Mechanical and Manufacturing Engineering department-Iraq. **Fig. 12** shows the result of the Charpy Impact Test conducted on Al alloy 2024 specimens, which were treated in Sunflower Oil and Artificially Aged at 180°C,195°C, and 210°C for 1, 2, and 4 hours. It can be seen in **Fig. 12** that the lowest Absorbed Impact Energy is 10.23 (J) for the sample Solution treated in Sunflower Oil and aged at 180°C for 1hr, while the Impact value of the annealed sample has a maximum Value of 19.8 (J) shown in **Table 3.**

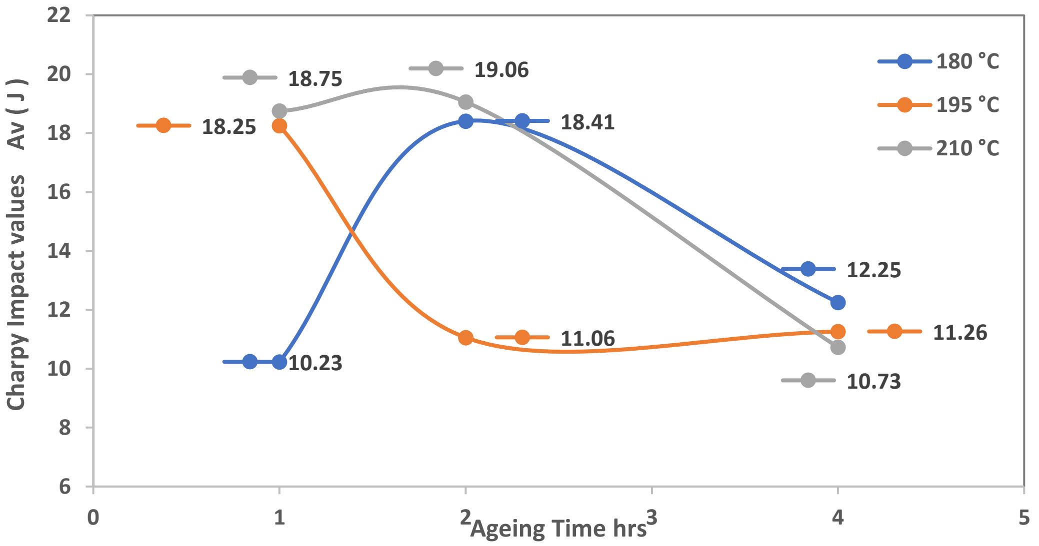


**Figure 12.** Charpy impact test for various ageing time and temperature curves for Al alloy 2024.

Here, the lowest Impact Energy, which is 10.23 (J), achieved at an ageing temperature of 180°C for 1hr, is considered the best result, the lowest impact energy means the specimen became more brittle than the annealed condition of the specimen associated with the highest hardness number and highest tensile strength. To be more convenient, **Table 4** below demonstrates the optimum Ageing time for all the ageing temperatures used in this study by showing Ultimate tensile strength, Hardness, and Impact values for each ageing temperature.

**Table 4.** Optimum Ageing Time and Overall Optimum Ageing Temperature for Al alloy 2024 Sunflower Oil.

| Optimum Ageing Temperature and Time | Hardness HRB | Tensile Strength $N/mm^2$ | Charpy Impact values Av (J) | Overall Optimum Ageing Temperature and Time |
|---|---|---|---|---|
| 180 °C / 1 hrs. | 82.53 | 579.97 | 10.23 | 180 °C / 1 hr. |
| 195 °C / 2 hrs. | 79.19 | 569.47 | 11.06 | |
| 210 °C / 4 hrs. | 78.36 | 569.72 | 10.73 | |

**Table 4.** demonstrates that the best ageing time for an ageing temperature of 180 °C is 1hr. Amongst (1,2,4 hrs.) is 2 hrs. for an ageing temperature 195 °C, while is the longest time 4 hrs. for an ageing temperature 210 °C. Here it can be noted that both the ageing time for ageing temperature 195 °C and ageing temperature 210 °C is longer and more time-consuming and still has not reached the maximum Hardness and Tensile strength of 180 °C is 1hr. which are 82.53 HRB and 579.97 N/mm$^2$, respectively. Consequently, according to the Ultimate tensile strength, Hardness, and Impact values, Overall Optimum Ageing Temperature and Time is 180 °C / 1 hr.

## 4. CONCLUSIONS

This study has examined how precipitation hardening affects the mechanical properties of Al alloy 2024 material. Solution Treatment and artificial ageing were conducted on an Al alloy 2024 sheet and round bar. The effects of solution treatment and ageing parameters on the mechanical properties of Al alloy 2024 were studied. The main points were concluded as follows:

1. Quenching medium played an important role, and Sunflower Oil resulted in the lowest impact value, 9.4 (J), compared to Sesame Oil and Corn Oil, 22.54 (J) and 20.16 (J), respectively.
2. According to the Tensile, Hardness, and Impact test results, the best ageing time for the ageing temperature, 180 °C, is 1hr., 195 °C, and 210 °C is 2hrs. and 4hrs. respectively.
3. The test results showed the best results of hardness and tensile strength. Which is achieved at 180 °C and 1hr. Ageing times are 82.53 HRB and 579.97 N/mm$^2$, respectively. These results are considerable enhancement in the mechanical property of the alloy achieved as compared to the annealing condition of the alloy, for the Hardness number value is more than three times and for the Tensile Strength value is more than the twice value. Furthermore, the result achieved for the Ultimate tensile strength is more than the As-received material's value.
4. The optimum condition amongst all the parameters which showed the best results of mechanical properties was obtained by 180°C at the lowest ageing time of 1hr. This means a cost-effective heat treatment as it needs the lowest time to achieve the best mechanical properties.

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## Credit Authorship Contribution Statement

Hawre F. Amin: Writing–review & editing, writing–original draft, heat treatment and mechanical tests. Abbas I. Khwakaram: mechanical tests. Rekawt R. Amin: heat treatment and mechanical tests. Pshtiwan M. Karim: mechanical tests. Omer S. Mahmood: review, heat treatment and mechanical tests.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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# تأثير إخماد الزيوت النباتية والتصلب بالترسيب على الخواص الميكانيكية لسبائك الألومنيوم (AA2024)

هاوري فتاح امين[1، *]، عباس ابراهيم خواكرم[1]، عمر صالح محمود[2]، بشتيوان محمد كريم[1]، ريكوت رشيد امين[1]

[1] جامعة السليمانية التقنية، المعهد الفني السليمانية، سليمانية، العراق
[2]جامعة السليمانية التقنية، الهندسة الميكانيكية والتصنيع، سليمانية، العراق

**الخلاصة**

توضح هذ البحث كيف أثرت معدلات التبريد المختلفة والتصلب بالترسيب على الخواص الميكانيكية لـ AA 2024. تم اختيار ثلاث عينات اختبارية، وتم إجراء المعالجة المحلولية عند درجة حرارة 500 درجة مئوية لمدة ساعتين، يليها التبريد في ثلاث وسائط تبريد مختلفة (زيت عباد الشمس، زيت السمسم، زيت الذرة). ونتيجة لذلك، أظهر زيت عباد الشمس أقل معدل لامتصاص الصدمات؛ ومن ثم، تم اختياره كوسيلة التبريد لهذه الدراسة. ونتيجة لذلك، تمت معالجة جميع عينات اختبارات الشد والصلادة والصدمات بمحلول عند درجة حرارة 500 درجة مئوية لمدة ساعتين، ثم تم إخمادها في زيت دوار الشمس إلى درجة حرارة الغرفة وتم تعتيقها صناعيًا عند درجة حرارة 180 درجة مئوية لمدة 1،2،4 ساعة، 195 درجة مئوية. درجة مئوية لمدة 1,2,4 ساعة، و210 درجة مئوية لمدة 1,2,4 ساعة. وقد لوحظت تحسينات كبيرة في المقاومة والصلادة مع انخفاض الليونة، وذلك بسبب إنتاج الحبوب المتناثرة بدقة. كان تصلب بالترسيب عند 180 درجة مئوية لمدة ساعة واحدة هو الإنجاز الأمثل الشامل، مما عزز UTS بنسبة 28.7٪ إلى 579 ميجا باسكال، مقارنة بالعينة المستلمة مع UTS 450 ميجا باسكال. بينما أدى التلدين إلى خفض UTS بنسبة 32.7% إلى 303 ميجا باسكال.

**الكلمات المفتاحية:** سبائك الألومنيوم 2024، المعالجة الحرارية، التصلب بالترسيب، التبريد، زيت عباد الشمس.