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# Effect of Retrogression Heat Treatment on Fatigue and Electrical Properties of 2024 Al alloy.

Hassan Zaid[1 *], Hassan haji[2]
Materials Science Department, University of Gharyan, Gharyan, Libya. hassan.zaid@gu.edu.ly
Materials Science Department, University of Gharyan, Gharyan, Libya. hahaji8888@gmail.com

*Corresponding author: hassan.zaid@gu.edu.ly

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## Abstract

The fatigue behavior of 2024 aluminum alloy is strongly influenced by heat treatment conditions, particularly T6 and retrogression and re-ageing (RRA) processes. In this study, specimens obtained from 2024 alloy plates were solution heat-treated at 520°C /2 h and subsequently aged to the T4 condition at 120°C/24 h. All samples were then subjected to a natural ageing (shelf life) period of 15 days before undergoing retrogression at approximately 220°C/3 min, followed by re-ageing at 165°C for 2h. The heat-treated samples were evaluated using tensile testing, electrical conductivity in %IACS and high cycle fatigue testing after all proposed heat treatment cycles. The samples were further tested under high-cycle fatigue conditions. The results indicate that both tensile properties and electrical conductivity were adversely affected after the 15-day shelf life. Distinct differences in fatigue behavior were observed between the retrogression and T6 (re-ageing) treated alloys. The retrogression treatment for a short time for the samples after 15 days, exhibited an improvement of mechanical strength and electrical conductivity. However, re-aging of these samples for 165/2hr shows beak strength with decrease in electrical conductivity. Although, T6 condition provides superior strength, the Retrogression treatment offers high fatigue performance by improving crack growth resistance, making it a more suitable choice for applications requiring enhanced fatigue durability.

**Keywords**: Retrogression and re-aging, Fatigue, Electrical conductivity, crack growth, Strength

## 1. Introduction

Aluminium–copper (Al–Cu) alloys, particularly the 2xxx series, are widely used in aerospace, transportation, and defence applications due to their high strength-to-weight ratio and good structural efficiency. Among these, 2024 aluminium alloy has gained attention for armed vehicles and structural components where a combination of strength, toughness, and fatigue resistance is essential [1,2]. However, the performance of these alloys under cyclic loading remains a critical concern, especially in applications subjected to repeated stress fluctuations over long service periods [3]. The mechanical and fatigue properties of 2xxx series alloys are strongly dependent on their heat treatment condition. The T4 temper, which involves solution heat treatment followed by natural aging, produces a fine dispersion of strengthening precipitates that results in peak strength [4]. Despite this advantage, T4-treated alloys are often susceptible to reduced resistance to fatigue crack propagation and environmental degradation, such as stress corrosion cracking [5]. This limitation has prompted the exploration of alternative heat treatment routes that can improve durability without significantly compromising strength.

Retrogression and re-ageing treatments have emerged as an effective method to modify the microstructure of Al–Cu alloys. In this process, a peak-aged alloy is briefly heated to an intermediate temperature (retrogression), causing partial dissolution and coarsening of precipitated particles, and is then re-aged to restore strength [6]. This treatment alters both the matrix and grain boundary precipitate structure, often resulting in improved resistance to crack growth and enhanced overall fatigue performance [7]. The modification of grain boundary precipitates from continuous to more discontinuous distributions is particularly beneficial in impeding crack propagation. Although Retrogression and re-ageing treatments have been widely studied for improving stress corrosion resistance, their influence on fatigue behaviour, especially in 2024 aluminium alloy, requires further investigation. In particular, the relationship between short retrogression times and fatigue crack growth behaviour under high-cycle loading conditions remains insufficiently understood [8,9]. Therefore, the present study aims to examine the effect of retrogression and T6 heat treatments on the fatigue properties of 2024 aluminium alloy. Samples initially treated to the T4 condition were aged for 15 days' period, then subjected to retrogression for a short duration (3 minutes at 220°C) followed by re-ageing (T6 at 165$^{o}$C for 2hr.). Fatigue behaviour for aged and re-aged samples was evaluated using high-cycle fatigue testing. The study focuses on comparing crack growth resistance and mechanical strength between the two conditions to better understand the trade-offs involved and to identify an optimal treatment route for improved fatigue performance.

## 2. Material and Methods

### 2.1 Materials.

This study utilized a rolled sheet 2024 aluminum alloy provided in dimensions of 3mm thickness and 600x800mm (in an annealed condition). The alloy material was supplied by the Applied Research Labs-Tripoli with the certified chemical composition as in Table 1.

Table 1: Chemical composition of 2024 studied Al alloy

| Element | Cu | Si | Mg | Mn | Cr | Zn | Fe | Al. |
|---|---|---|---|---|---|---|---|---|
| % | 4.62 | 0.51 | 1.53 | 0.61 | 0. 1 | 0.24 | 0.56 | Bal. |

### 2.2 Heat Treatment

As received sheet of 2024 Al-Cu was cut and machined to form 15 tensile samples prepared according to ASTM-E8 standards. The samples were taken to a muffle furnace (Figure 1) for solution heat treatment at 520$^{o}$C for 2 hours followed by water quenching. In order to study

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the effect of natural aging time on mechanical and electrical properties, the studied samples in tensile samples shape were divided in to three groups in experimental plane (Figure 2) as in Table 2:

Table 2: Studied samples in different groups

| Group | case | Heat treatment | |
|---|---|---|---|
| 1 | Solution treated then aged (T4) | 120ºC/24hr | Air cooling |
| 2 | Stored for 15 days, then (re-aging) | 220ºC/3min | Air cooling |
| 3 | Retrogression after re-aging (RRA) | 165ºC/2hr | Furnace cooling |

Figure 1: Muffle Furnace used for the heat treatment

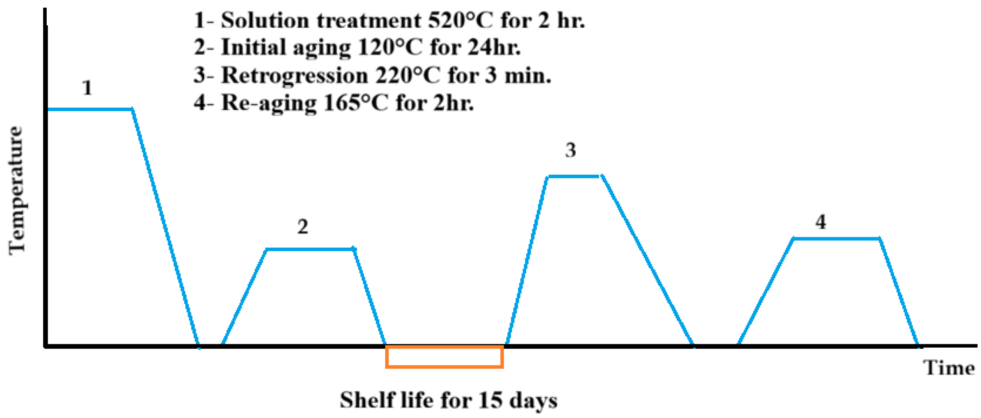


Figure 2: Schematic of Experimental plane for the studied samples.

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### 2.3 Tensile tests

Three groups of 5 ASTM tensile samples (E-8), were taken to the Servo-Hydraulic tensile testing machine Zwick-SP1000. The aim was to evaluate the tensile strength at different heat treatment conditions, and to set up the maximum strength to failure in MPa.

### 2.4 Electrical Conductivity

All treated samples were surface-cleaned, and then one sample from each studied group was taken for electrical conductivity measurement in units of the International Annealed Copper Standard (IACS) as shown in Figure 3.


Figure 3: Standard sample for electrical conductivity measurement, b) Electrical conductivity readings for RRA sample.

### 2.5 Fatigue tests

The three group samples were surface-ground and polished to a mirror-like finish to eliminate any influence of surface scratches on the fatigue test results. Three groups of fatigue samples according to ASTM standards (E-466) were tested in High Cycle fatigue (HCF) Figure 4. The fatigue tests were carried out by applying a periodic axial load of constant amplitude with a stress ratio ($R = \frac{S_{min}}{S_{max}}$) of 0.1 and a frequency of 15 Hz. As a criterion for the end of the fatigue tests, the fracture surface of the broken samples at $2x10^3$ cycle were considered. (the end of the test is set to this value for those samples that were not previously broken).

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Figure 4: Fatigue test machine used in the study.

## 3. Results and Discussion

### 3.1 Tensile Properties

Five ASTM E-8 tensile samples were used for each case, tensile strength results showed sharp increase of ultimate tensile strength after normal aging T4 of the solution treated samples (Figure 5), which reflects the refining and coarsening of the precipitated particles after different heat treatment regimes.

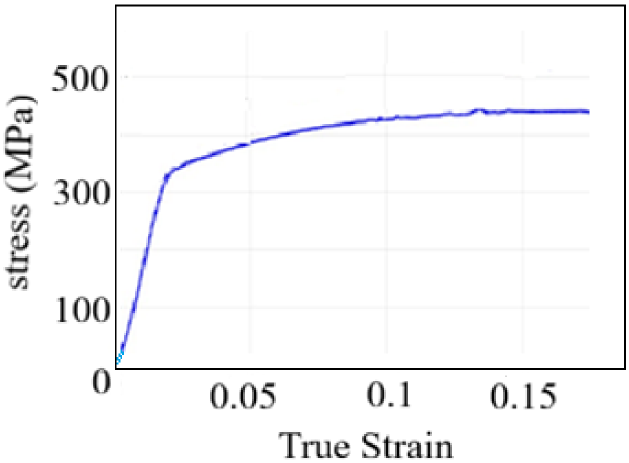


Figure 5: Tensile strength of 2024-T4 samples.

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On the contrary, after extended natural aging for 15 days, a slight reduction in strength was observed as shown in Figure 6. This behaviour can be explained by the gradual transformation of fine precipitates into coarser and less coherent phases, reducing their strengthening efficiency.

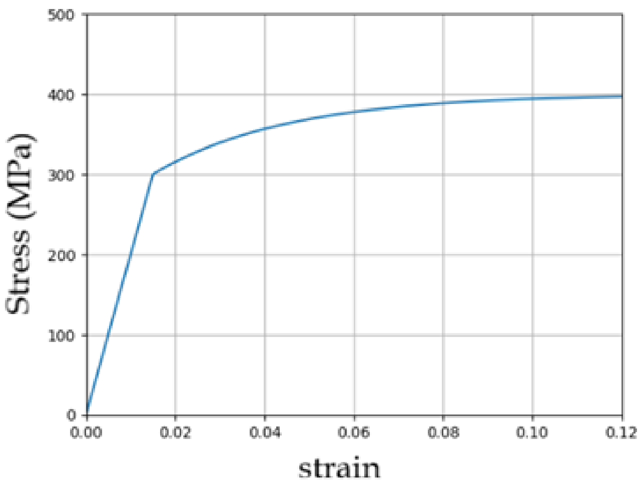


Figure 6: Tensile strength after 15 days.

To improve tensile strength, a retrogression treatment (Ret.) at 220°C for a short duration of 3 minutes was applied. This treatment resulted in a slight increase in strength of about 12% of T4 treatment, which is expected due to the redistribution and refinement of precipitates. Final mechanical properties have been resulted after re-aging treatment (T6) of 165ºC/2hr for the retrogression samples, and good improvement of strength was observed as shown in Figure 7.

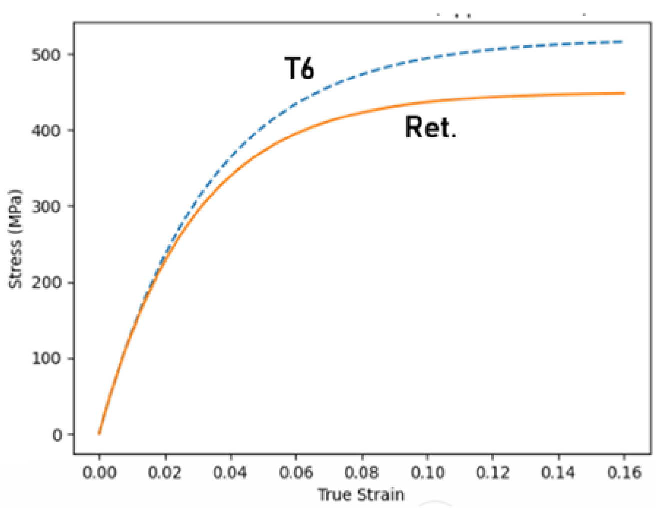


Figure 7: Change in strength of RA samples after retrogression.

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The tensile test results demonstrate a clear dependence of mechanical properties on the applied heat treatment conditions. The solution-treated and naturally aged (T4) samples exhibited a noticeable increase in ultimate tensile strength (UTS), which can be attributed to the formation of finely dispersed second-phase coherent precipitates, including uniformly distributed Guinier–Preston (GP) zones. These microstructural features effectively impede dislocation motion, thereby enhancing strength. Prolonged natural aging for up to 15 days resulted in over-aging, characterized by the coarsening of fine precipitates and a partial loss of coherency between the precipitates and the aluminum matrix. This microstructural evolution led to a reduction in tensile strength by approximately 10%. The application of retrogression treatment (Ret.) for a short duration, followed by artificial aging for 2 hours (T6), resulted in a significant increase in UTS compared to the peak T4 condition. This improvement is attributed to the refinement and re-distribution of precipitates, along with enhanced coherency with the matrix. The retrogression and re-aging (RRA) treatment is also known to improve additional properties such as fatigue resistance, although this may sometimes occur with a slight compromise in strength, as summarized in Table 3. Overall, the tensile results confirm that precipitation hardening plays a dominant role in controlling the strength of the 2024 aluminum alloy, with peak strength achieved under optimal aging conditions.

### 3.2 Electrical Conductivity

The variation in the electrical conductivity of the 2024 alloy during aging treatments is related to the way in which Cu and Mg elements are organized in the microstructure and how it affects the electro-scattering [10]. IACS measurements show, a rapidly increasing of electrical conductivity at early aging times and gradually approaches a saturation value at longer aging durations, reflecting the progressive depletion of solute copper atoms from the aluminium matrix [11]. The electrical conductivity measurements for the studied samples showed a strong correlation with the aging condition of the alloy. The T4 samples exhibited a conductivity of approximately 35 IACS%. However, after 15 days of shelf life the electrical conductivity was found in a range of 40-45 IACS, which is expected due to growth of precipitates thereby a minimal Cu in the matrix. As samples were aged (retrogression) and then re-aged (T6), electrical conductivity was slightly decreased to a minimum of 28 IACS%. This reduction is attributed to the increased number of solute atoms and fine precipitates within the aluminium matrix, which thus maximizing their scattering effect and reduce conductivity. A summary of effect of aging treatment on tensile strength and electrical conductivity results as in Table 3.

These results are exactly matched with what was found in other previous studies and confirming that electrical conductivity is a sensitive indicator of microstructural evolution during aging treatments.

Table 3: Change in tensile strength due to aging treatment [10, 11, 12]

| Condition | UTS (MPa) | Expected IACS% | Remarks |
|---|---|---|---|
| **Solution treated** | 400 | 28-32 | Normal value |
| **T4 (natural aging)** | 448 | 30-35 | Moderate UTS and IACS |
| **Re-aging after 15 days** | 400 | 40-45 | Over aged →high IACS |
| **Retrogression (Ret.)** | 450 | 32-36 | Increase in UTS → increase in IACS |
| **Re-aging (T6)** | 510 | 28-32 | Peak UTS→Low IACS |

### 3.3 Fatigue behaviour

The fatigue performance of the 2024 aluminium alloy was strongly influenced by the heat treatment condition. Two treatment conditions were studied as T4 and RRA (samples after T6 treatment) condition. The S–N curves for both T4 and RRA samples exhibited the typical inverse relationship between applied stress and number of cycles to failure, following Basquin-type behaviour.

For the RRA condition, the fatigue life was consistently higher across all stress levels. For example, at an applied stress of 128 MPa, the T4 samples endured approximately $7\times10^4$ cycles, whereas the T4 samples failed at about $5.3\times10^4$ cycles. A similar trend was observed at higher stress levels, indicating superior fatigue resistance in the RRA condition.

In many studies, Fatigue behavior can be blotted in log-log coordinates, as S-N data which then can be reasonably approximated by straight lines. The fatigue results are reasonably following the Basquin-type decay with the power relationship of the general form (Basquin's equation), Eq. 1.

$$\sigma_{max} = A\left(2N_f\right)^b \tag{1}$$

Where $\boldsymbol{\sigma_{max}}$ is the tensile strength, $\boldsymbol{A}$ is related to the fatigue strength coefficient, $\boldsymbol{N_f}$ is the number of cycles to failure, and $\boldsymbol{b}$ is the fatigue strength exponent. Basquin's equation is a power-law relationship used to model high-cycle fatigue life on a stress-life (S-N) for the data in the following fatigue results and as blotted in Figure 7.

- Fatigue results for 2024-RRA samples:

| Stress (MPa) | Number of cycles |
|---|---|
| 128 | $7X10^4$ |
| 133 | $6.5x10^4$ |
| 141 | $6x10^4$ |
| 160 | $4.5x10^4$ |
| 180 | $3.8x10^4$ |
| 220 | $2x10^4$ |

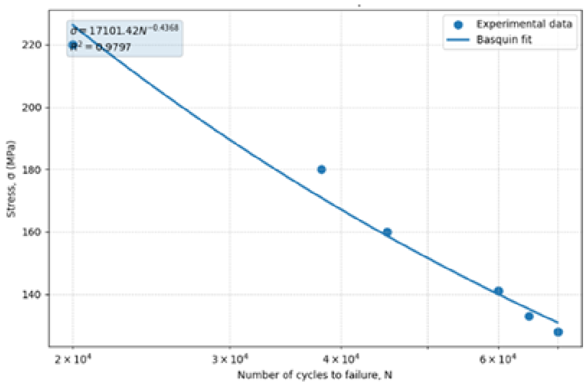


Figure 7: S-N curve with Basquin fit for 2024-RRA Tempered Fatigue tests.

The fitted relationship is:

$$log_{10}\ (S) = a + b\ log_{10}\ (N) \quad (2)$$

Where a = 17101.42MPa, b = - 0.4368

Or in standard Basquin form:

$$S =\ 10^{17101.42}\ .N^{-0.4368} \quad (3)$$

The negative slope of the fit equation confirms the expected fatigue behavior in this case.

- Fatigue results for 2024-T4 Tempered samples: the results were analyzed from the following fatigue results and as plotted in Figure 8.

| Stress (MPa) | Number of cycles |
|---|---|
| 128 | $5.3X10^4$ |
| 133 | $1.7x10^4$ |
| 141 | $6.2x10^3$ |
| 160 | $4.0x10^3$ |
| 180 | $3.1x10^3$ |
| 220 | $1.8x10^3$ |

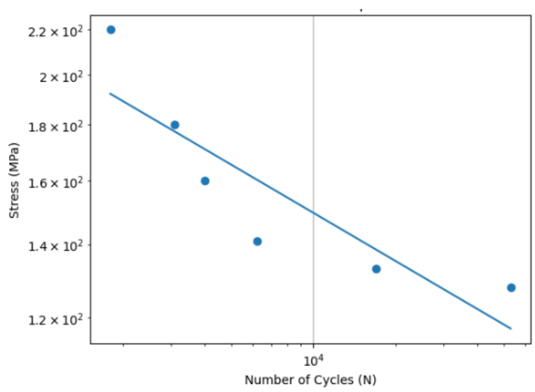


Figure 8: S-N curve with Basquin fit for 2024-T4 Fatigue tests.

For the retrogression case: the value of a = 2.742 and b = - 0.139 in the form of:

$$s = 10^{2.742} \,.\, N^{-0.139} \quad (4)$$

The larger the slope number, the steeper the line. Therefore, (-0.139) in T4 is steeper than RRA condition, it shows the improved fatigue resistance of RRA, Therefore, RRA treatment improves the crack growth resistance in the heat treated 2024 Al alloys.

The RRA-treated samples exhibited superior fatigue strength compared to the T4 condition under high-cycle fatigue loading. This improvement is attributed to the optimized precipitate structure, which enhances resistance to crack initiation and propagation, leading to improved fatigue performance despite only moderate changes in tensile strength.

The Basquin fit of the S–N data further confirms this trend, with the T4 condition showing a slightly steeper slope, indicating a faster degradation of fatigue strength with increasing cycles.

In overall, the reduction in fatigue life for RRA-treated samples can be attributed to microstructural changes induced by re-aging. The coarsening of precipitates reduces their effectiveness in impeding dislocation movement and crack initiation. Additionally, larger precipitates may act as stress concentration sites, facilitating earlier crack nucleation under cyclic loading.

### 3.4 Correlation Between Mechanical and Electrical Properties

A clear relationship between tensile strength, electrical conductivity, and fatigue behaviour can be observed. The T4 condition, characterized by fine and coherent precipitates, provides moderate strength and good electrical conductivity. Samples after prolonged aging time for 15 days show a reduction in strength, increased in electrical conductivity, but less fatigue resistance. On the other hand, the RRA condition shows improved conductivity due to precipitate resizing, but this comes with increase in strength and improved fatigue resistance, but lower electrical conductivity.

This trade-off highlights the importance of optimizing heat treatment parameters depending on the intended application. For structural applications requiring high fatigue resistance, the T4 condition is preferable, whereas RRA treatment may be advantageous where higher conductivity and improved corrosion resistance are required.

## 4. CONCLUSION

The experimental results demonstrate that:

- Improving of the mechanical performance was achieved in the T4 condition, primarily due to the presence of finely distributed precipitates.

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- Prolonged aging led to precipitate coarsening, resulting in reduced strength and fatigue life, accompanied by an increase in electrical conductivity. This effect was partially mitigated by the application of short-time retrogression treatment.
- Peak mechanical performance was achieved in the T6 condition, where finely precipitates are redistributed.
- Electrical conductivity increased with precipitate coarsening, indicating a reduction in solute content within the aluminum matrix.
- The re-aging treatment (165°C for 2 h) produced high strength suitable for improved fatigue resistance, although it resulted in relatively lower electrical conductivity.
- Fatigue performance was found to be highly sensitive to microstructural evolution and followed Basquin's law behavior. This trend was particularly evident in RRA-treated samples, where enhanced fatigue resistance was associated with lower IACS values.

Overall, these findings highlight the critical role of precipitation kinetics in tailoring the mechanical, electrical, and fatigue properties of 2024 aluminum alloys.

## 5. Future studies

This study will be followed by an investigation of the strengthening mechanisms during aging and re-aging treatments. The focus will be on precipitated particles (second phase), including their size, chemical composition, volume fraction, and distribution. These characteristics will be analysed using SEM-EDX and TEM techniques to provide a comprehensive understanding of how this heat treatment regime affects the mechanical properties of high-strength aluminium alloys.

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