Fatigue 2010

Influence of heat treatment on the fatigue behaviour of two aluminium alloys 2024 and 2024 plated

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Received 28 February 2010; revised 10 March 2010; accepted 15 March 2010

Abstract

In the present work, the influence of the heat treatment on the evolution of oligocyclic fatigue life on two types of aluminium alloys was studied. The two alloys (2024 and 2024 plated by 1050) are largely used in the aircraft industry because of their good mechanical characteristics and their lightness. The main factor of heat treatment influencing fatigue behavior in these two types of alloys is the precipitation of Al\textsubscript{2}Cu in the 2024 alloy and diffusion of cupper from the middle to the surface in the 2024 plated one. Our work is to locate the effect of heat treatments on different microscopic characteristics and their influence on the evolution fatigue damage, the idea of using heat treatments is based on their role to change the precipitation and the direction of diffusion on those alloys. The results obtained showed that we can increase the fatigue performance in 2024 alloy of about 34 % just by using different age hardening, so this process of age hardening can be envisaged to increase the fatigue life of aluminium components when these are submitted to fatigue loading, however, in the case of 2024 plated alloy, the diffusion phenomenon has made their surface very fragile, what led to the reduction in their lifespan. Microstructural investigations, such as scanning electron microscopy and micro hardness, were carried out in order to observe the microstructural evolution due to heat treatment and fatigue.

Keywords: fatigue life, hardness, heat treatment, 2024 and 2024 plated alloys.

1. Introduction

Aluminium alloys of the 2XXX series are widely used in aeronautical applications due to the high strength associated with low density and good fracture toughness [1, 2]. Among these alloys, the quaternary Al–Cu–Mg–Mn 2024 alloy is one of the most used [3]. Despite its large use in aircraft structural parts and the plenty of literature data available about its mechanical properties, the effect of a heat treatment on fatigue life has not been deeply investigated.

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Fatigue life of a material can be divided into a number of subsequent fatigue damage phases, characterized by cyclic slip, crack nucleation, micro-crack growth and macro-crack growth up to the final material failure. Yet, although considerable progress has been made in understanding the mechanisms of fatigue failure, an accurate fatigue failure prediction is difficult because the different physical processes which prevail to the gradual fatigue damage accumulation during the fatigue life of a metallic component are complex and interrelated [5]. Develop with increasing number of fatigue cycles from atomic to macro-scale damage mechanisms and also entail a host of material, geometric and loading parameters [4]. Cyclic plasticity of engineering polycrystalline alloys is complex and depends on a host of parameters including type of unit cell, value of stacking fault energy, heat treatment, grain size, precipitate geometry and size, distribution and coherence to the matrix etc. [5, 6, 7]. In precipitation hardened alloys, cyclic hardening occurs due to an increase in dislocation density and dislocation-precipitate interactions. Hence, cyclic hardening is highly favored if the precipitates in the age-hardened alloy are not easily shearable by the dislocations. This is the case for the Al–Cu alloys, like the investigated 2024, containing non-shearable \((\text{Al}_2\text{Cu})\) precipitates.

The formation, growth, and coalescence of interfacial voids in the static fracture process of metallic materials have been frequently observed and extensively investigated by numerous researchers [10, 11]. Voids were also noticed on fatigue fractures in 2XXX series aluminium alloys [12, 8]. Al-alloys, such as 2024 (T3), 7075 (T6), and 6061 (T6) contain numerous constituent particles of brittle phases dispersed in the ductile matrix, which play an important role in void formation [13, 14]. When ductile materials are subjected to static or cyclic loads, the fatigue (ductile) fracture may result from the nucleation, growth and coalescence of micro-voids. The required design lifetime of many engines, wheels, chassis, and body components often exceeds \(10^8\) cycles (gigacycle range) [9, 15]. In recent years, there has been a development of interest in studying very long life fatigue behavior (between \(10^7\) and \(10^{10}\) cycles), especially of various high strength steels [15, 16].

2. Experimental procedure

2.1. Material and specimens

The investigations were conducted for the aircraft structure aluminum alloys, it was provided by Algerian Air Force. Exactly, the materials used in this study are 2024 and 2024 plated aluminium alloys with a thickness of 03 mm. The mechanical properties and the chemical composition of the materials are shown in Tables 1 and 2, respectively.
Table 1. Mechanical properties

<table>
<thead>
<tr>
<th>Material</th>
<th>$E$ (GPa)</th>
<th>$\sigma_{\text{max}}$ (MPa)</th>
<th>$\sigma_{0.2}$ (MPa)</th>
<th>Hardness (Hv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024</td>
<td>75</td>
<td>418</td>
<td>271</td>
<td>149</td>
</tr>
<tr>
<td>2024*</td>
<td>72</td>
<td>365</td>
<td>205</td>
<td>175</td>
</tr>
</tbody>
</table>

2024*: Duralumin plated by 1050
And the hardness of the 1050 is 44 Hv.

Table 2. Chemical compositions (mass %)

<table>
<thead>
<tr>
<th>Material</th>
<th>Cu</th>
<th>Mg</th>
<th>Mn</th>
<th>Fe</th>
<th>Si</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024</td>
<td>4.49</td>
<td>0.71</td>
<td>0.63</td>
<td>0.37</td>
<td>0.48</td>
<td>Bal.</td>
</tr>
<tr>
<td>2024*</td>
<td>4.25</td>
<td>0.78</td>
<td>0.79</td>
<td>0.39</td>
<td>0.43</td>
<td>Bal.</td>
</tr>
<tr>
<td>1050</td>
<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
<td>0.35</td>
<td>0.01</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Fatigue testing specimens were machined in the long transverse (LT) direction, as shown in Fig. 1. The grinding was always performed parallel to the longitudinal direction of the specimens. Axial fatigue tests were conducted on flat dog-bone specimens.

![Fatigue test specimen](image)

Prior to testing, all specimens of 2024 plated alloy have been heat treated in order to ensure almost the same mechanical and “metallurgical” initial state. The applied thermal cycle is composed of a heating until 520 °C followed by a holding time of 1 h at this temperature and; finally, a slow cooling until the room temperature. Again, the fracture surface of 2024 plated alloy in traction test, have been carried out by SEM (Fig. 2), we have a faceted appearance of ductile rupture.

2.2. Fatigue tests before applying heat treatments

These tests were done under a constant amplitude sinusoidal wave loading between 360 and 400 MPa for the 2024 and between 330 and 350MPa for the plated one (oligocyclic fatigue). The tests were carried out using MTS servo-hydraulic machine, interfaced to a computer for machine control and data acquisition. All tests were done at a frequency of 20Hz in air under room temperature that ranged from 20 °C to 25°C with a relative humidity from 50% to 60%.
The first results of these tests are given in Table 3, we retain only the average of all the tests. They are given by number of cycles until rupture.

![Image of a micrograph obtained by a scanning electronic microscopy (SEM) with a magnification of 200 X, showing a ductile rupture.]

**Table 3. Fatigue lifespan**

<table>
<thead>
<tr>
<th>Material</th>
<th>Number of cycles (N&lt;sub&gt;r&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024</td>
<td>38207</td>
</tr>
<tr>
<td>2024 Plated</td>
<td>50855</td>
</tr>
</tbody>
</table>

After having seen the fatigue lifespan of the two alloys in the initial state, we try to investigate the evolution of these lifespan when we make changes in the microstructure of the material. Furthermore, we will study the effect of the heat treatment parameters, such as maintaining time and maintaining temperature on the evolution of lifespan.

### 2.3. Heat treatments effects

#### 2.3.1. Case of 2024

Before performing the tests, all 2024 specimens have been heat treated in the following thermal cycle: Heating until 500 °C followed by a holding time of 24 minutes at this temperature and; finally, a speedy cooling in cool water until the room temperature. After that, we will carry out the following tests:

- Effect of maintaining temperature: We have used four (04) batches in different levels of temperature; in each batch we have five (05) specimens. The following values in °C of the temperature were applied with a maintaining time of fifteen (15) minutes: 200, 230, 260 and 290 °C.
- Effect of maintaining time: The same tests as the precedents were done on four (04) batches of five (05) specimens each one. The following values in minutes of the time were applied with a maintaining temperature of 230 °C: 15, 30, 45 and 60 minutes.

We point out that the cooling of the specimens was done in the ambient air.

#### 2.3.2. Case of 2024 Plated

- Effect of maintaining temperature: We have used eight (08) batches in different levels of temperature; in each batch we have eight (08) specimens. The following values in °C of the temperature were applied with a maintaining time of 30 minutes: 350, 370, 390, 410, 430, 450, 470 and 490 °C.
- Effect of maintaining time: The same tests as the precedents were done on eight (08) batches of eight (08) specimens each one. The following values in minutes (min) of the time were applied with a maintaining temperature of 500 °C: 30, 50, 70, 90, 110, 130, 150 and 170 minutes.
The cooling of the specimens was in the same manner with those of 2024.

3. Results and discussion

3.1. Case of 2024

Before giving the results of the above tests, and in order to see the contribution of the annealing heat treatment in the behavior of 2024 in mechanical fatigue, we have carried out an annealing in five (05) specimens of one hour in 520 °C and cooled in the furnace.

After that, the specimens were cycled between 360 and 400 MPa, but the obtained results were very disappointing. Moreover, the longest fatigue lifespan obtained in these specimens was 997 cycles, so comparatively with the initial lifespan, we have a loss of 98% in the number of cycles.

This observation may indicate that is very important to avoid this kind of heat treatment when the 2024 alloy is subjected to a cyclic loading.

The second part of results is those given after applying the heat treatments performed in section 2.3.1, we gather them in the following figure.

![Fig.3. Evolution of the 2024 lifespan according to the maintaining temperature.](image)

In general, the gain in the fatigue life is due to the hardening or softening of the material. Applying a heat treatment led to the formation of other phases more or less hardening.

When the alloy is carried at the temperature 500°C, this one will be subjected to a treatment of setting in solution, which generates the dissolution of the hardening elements. But if we try to maintain these hardening elements in home temperature by cooling in cold water, they will be in “metastable” form and the hardening elements will have big sizes, thus the material becomes very fragile. To avoid this phenomenon, we carry out another kind of heat treatment, which consist on crystallization of the Al₂Cu in specific conditions of time and maintaining temperature, these microscopic evolutions contribute on the change of macroscopic behaviours of the alloy such as fatigue life and hardness.

The effect of the maintaining temperature on fatigue life is shown on figure 3, where we can remark that the maximum on lifespan is reached at 200 °C. On the other hand, we have obtained the lowest value in lifespan at 260 °C, so that a diminution of half in the fatigue life comparatively with the first one where we have a fatigue life of 60 000 cycles.

The effect of the maintaining temperature on hardness must also be announced (Fig. 4), we remark that have an increase followed by a decrease of the hardness, the temperature of 230 °C can be taken as the place where the hardness reaches the maximum of 133 Hv.
In the other hand, the effect of maintaining time in the heat treatment temperature is very significant, especially in terms of fatigue life. The following figure show the evolution in decrease of the fatigue life when the maintaining time is in increase, thus can be explained by the growth of the precipitate sizes. Hence, the interfaces between the precipitates and the principal phase increase, those interfaces will be tolerable to have initiation of the cracks.

The optimum time of maintaining temperature which will be taken in the heat treatment is 15 minutes. The average fatigue life of the specimens obtained was 50,000 cycles.

For the effect of the maintaining time in the hardness of the alloy, is also significant where can obtain a maximum of the value at 30 minutes of maintaining time (Fig. 6).

3.2. Case of 2024 plated

For the behavior of the 2024 plated alloys towards the heat treatments should be have the same response, but in spite of the very thin coating, the results were not similar with those of the 2024. Indeed, the next figures show the results obtained in this second alloy.
In figure 7, we remark that the maintaining temperature have a great effect on the behavior of the fatigue life evolution, the ideal temperature to increase this lifespan is 350 °C, after that we have a strong reduction on fatigue life followed by a slight augmentation and reduction.

Fig.6. Evolution of the 2024 hardness according to the maintaining time.

In the following figure (Fig. 8), we have a mapping of the hardness on all over the thickness and on different temperature of the plated alloy. We remark that the hardness of the material is very influenced by the maintaining temperature in the oven. When the temperature is low (350 °C), we have a great difference in hardness between the middle and the surface, but when this maintaining temperature is high (490 °C) we obtain just a slight difference in hardness between the two last places, we remark also that the hardness tends to stabilized in all over the thickness around 75Hv.

These macroscopic observations can be explained by the diffusion phenomena. So when the temperature of the treatment is high, we will have a strong agitation of the aluminium atoms and facilitate their displacements from the surface to the middle and the same for the copper atoms which take the opposite direction, this process led to homogenization in hardness of the material, but the alloy will be weakened which decrease its fatigue life.

Fig.7. Evolution of the 2024 plated fatigue life according to the maintaining temperature.
The same behavior was observed when we were studying the effect of the maintaining time in the evolution of the hardness and in the fatigue life, but a slight difference in the second part of the test was obtained. Indeed, the fatigue life increases in (Fig. 9) and becomes lower than the first one (Fig. 7).

If an eventual heat treatment is occurred, the optimum maintaining time will be half hour (30 min), the fatigue life obtained in this case is 18000 cycles.

In the next figure (Fig. 10), we realized a mapping of the hardness on all over the thickness and on different temperature of the plated alloy. We remark the same evolution with those obtained in 2024.

The hardness of the material is very influenced by the maintaining time in the oven, when the time is low (30 min), we have a great difference in hardness between the middle and the surface, but when this maintaining time is high (170 min) we obtain just a slight difference in hardness between the two last places, we remark also that the hardness tends to stabilized in all over the thickness around 95 Hv.

In difference with 2024, we can remark that the hardness of the surface (in 2024 plated alloy) increases strongly from 44 Hv of the initial state to 95 Hv, this led to the fragilization the 2024 plated surface and become privileged zones to the crack initiation. Therefore, its fatigue life decreases strongly.
4. Conclusion

Fatigue tests of un-notched dog-bone flat specimens machined from 2024 and 2024 plated aluminium alloy plate were carried out in air and at room temperature. An increase in fatigue life was found with applying a specific heat treatment in terms of maintaining temperature and time in the furnace. This was attributed to microstructural changes that anticipate the crack initiation during the fatigue testing. Furthermore, a very fine precipitate obtained in the 2024 material make this fatigue life more important, on the other hand, the diffusion of the copper from the middle of the 2024 alloy to the surface, affect the material and makes it weaker in terms of fatigue life.

Acknowledgements

The authors gratefully acknowledge the support of ERMaéro unit for performing this work.

References


