Fatigue Life Assessment of 2024 Aluminum Alloy Specimens by means of Hardness Measurements at the Meso Scale

By

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Introduction

- Failure by fatigue remains the most serious concern for structural failure of aircraft components despite the exhaustive amount of past research.

- An accurate fatigue failure prediction is difficult:
  - different physical processes which are complex and interrelated, develop with increasing number of fatigue cycles from atomic, over nano-, meso- and micro-, to macro-scale damage mechanisms,
  - entail a host of material, geometric and loading parameters.
Introduction (continued)

- Damage tolerance which is the present day design concept for modern metallic aircraft structures, relies on fracture mechanics, i.e. accounts for fatigue damage accumulation after the structure under consideration involves fatigue macro-cracks.

- Growth of a fatigue macro-crack represents the last stage of the entire fatigue damage accumulation process which refers to a small percentage of the material’s fatigue life.

- The increasing trend in aeronautical industry to replace the existing differential by integral structures makes the need to early detect possible fatigue damage urgent.
Present Work

- **The objective of the present work**, is to exploit the ability of measuring material hardness changes at the nano- and meso-scale in order to develop a concept for the early detection of fatigue damage accumulation for the aircraft aluminum alloy 2024 T3.

- To accomplish the above objective interrupted fatigue tests at $R=0.1$ followed by hardness measurements at the mesoscale were conducted.

- The determination of the specimen hardness was carried out by means of nanoidentations.

- The evolution of the surface hardness with increasing number of fatigue cycles has been monitored.

- The effect of the applied fatigue stress value on the surface hardness change has been accounted for.
Basic Considerations

- Cyclic plasticity at the near surface material layers at the atomic-, nano- and meso-scale is prevailing damage mechanism at the early stages of high cycle fatigue damage accumulation.

- The convention adopted in the present investigation for the scales is: $1 \times 10^{-4}$ to $1 \times 10^{-3}$ µm atomic-scale, $1 \times 10^{-3}$ to $1 \times 10^{-1}$ µm nano-scale, $1 \times 10^{-1}$ to 10 µm meso-scale, 10 to 200 µm micro-scale and >200 µm macro-scale.

- Cyclic loading of metals leads to the formation of bands of concentrated slip.

- Cyclic slip occurs almost immediately after a cyclic stress above the fatigue limit is applied.

- The occurrence of surface slip markings lying along traces of the active slip planes is a general feature of cyclic plastic deformation.
Basic Considerations

- Not all metals subjected to cyclic loading harden, as cyclic softening has been observed as well.

- Cyclic plasticity of engineering polycrystalline alloys is complex, thus making the prediction of the mechanisms of cyclic damage and the associated cyclic hardening or softening difficult.
Basic Considerations

- With regard to the engineering alloy under consideration and the aims of the present study the following observations are of importance:
  - Experiments on FCC single crystals subjected to fully reversed fatigue loading, have shown a rapid hardening already in the initial few cycles.
  - The high value of stacking fault energy favors the activation of multiple glide systems and the formation of three-dimensional dislocation structures, which result in cyclic hardening during plastic deformation.

- In precipitation hardened alloys, cyclic hardening occurs due to an increase in dislocation density and dislocation – precipitate interactions.

- 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 \(\theta\) (Al\(_2\)Cu) precipitates.

- Available experimental data for the 2024 T4, 7075 T6 aluminum alloys showed cyclic hardening due to cyclic loading.
Basic Considerations

- Microhardness measurements by means of Vickers micro-hardness tests conducted on 2024 T4 alloy specimens fatigued at reversed bending have confirmed the increase of hardness at the microscale following fatigue loading.

- As changes are limited within a narrow surface material layer classical hardness measurements lack the necessary sensitivity to reliably quantify this phenomenon.

  the use of **mesohardness** measurements overcomes this disadvantage.
Experimental investigation

Experimental conditions

- **Material**
  Sheet 2024 T3 aluminum alloy of 3mm nominal thickness

- **Fatigue tests (ASTM E466)**

- **Locations of hardness measurements**
## Experimental investigation (continued)

### Experimental conditions

<table>
<thead>
<tr>
<th>Specimen Nr.</th>
<th>Maximum applied stress $\sigma_{\text{max}}$ [MPa]</th>
<th>Selected numbers of cycles for interrupting the fatigue tests</th>
<th>Expected fatigue life according to [17]</th>
<th>Estimated percentages of expected fatigue life [%]</th>
<th>Experimental fatigue life $N_r$ [cycles]</th>
<th>Consumed percentages of fatigue life corresponding to the experimental fatigue lives [%]</th>
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<tbody>
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<td></td>
</tr>
</tbody>
</table>
Experimental investigation (continued)

Experimental conditions

- **Mesohardness measurements**

![Diagram](image-url)
Experimental results

Fatigue tests

\[
\sigma_{\text{max}} = c_1 + \frac{c_2 - c_1}{e^{(\log N/c_3)^{c_4}}}
\]

<table>
<thead>
<tr>
<th>Fitting Coefficient</th>
<th>Value of the coefficient</th>
</tr>
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<td>( c_1 )</td>
<td>182.60</td>
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<tr>
<td>( c_2 )</td>
<td>425</td>
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<tr>
<td>( c_3 )</td>
<td>5.09</td>
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<tr>
<td>( c_4 )</td>
<td>7.29</td>
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</tbody>
</table>

Maximum applied stress - \( \sigma_{\text{max}} \) [MPa]

Number of cycles to failure - \( N_f \) [cycles]
Experimental results

Hardness measurements

Nanoindentation results conducted in the unloaded area 1

Measurement areas and corresponding nanoindentation results for one specimen before fatigue loading
Experimental results

Stress field in the specimens at various loads

- $F_{\text{max}} = 4.85\text{kN}$
- $F_{\text{max}} = 5.40\text{kN}$
- $F_{\text{max}} = 6.75\text{kN}$
Experimental results

Nanoindentation depth results in all areas examined at various operational cycles – *Maximum stress at area 4: $\sigma_{\text{max}} = 180 \text{ MPa}*
Experimental results

Nanoindentation depth results in all areas examined at various operational cycles – Maximum stress at area 4: $\sigma_{\text{max}} = 200 \text{ MPa}$
Experimental results

Nanoindentation depth results in all areas examined at various operational cycles – \( \text{Maximum stress at area 4: } \sigma_{\text{max}} = 250 \text{ MPa} \)

\[ \sigma_{\text{local}} = 78 \text{ MPa} \]

\[ \sigma_{\text{local}} = 160 \text{ MPa} \]

\[ \sigma_{\text{local}} = 250 \text{ MPa} \]

Area 2

Area 3

Area 4
Experimental results

Indentation depth alteration versus the operational cycles at various specimen areas and loads

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Experimental results

The observed hardness behaviour may be expressed by empirical equations of the form

\[ h_p = P_1 + P_2 \cdot e^{\left(-\left(\frac{n}{N_f}\right)\right)} \]

- \( h_p \): remaining penetration depth after the load is fully removed,
- \( n/N_f \): consumed percentage fatigue life
- \( P_1, P_2 \) and \( P_3 \): material and fatigue stress dependent constants
Conclusions

- The surface hardness of the alloy 2024 increases at different rates depending on the applied fatigue stress and number of applied fatigue cycles.
- The dependency of indentation hardness increase on the number of fatigue cycles is non-linear and seems to tend to a hardness saturation value.
- The surface hardness increase process is accelerated at higher fatigue stress amplitudes.
- Further experimental investigation is needed to derive reliable equations of the evolution of hardness increase with the number of applied fatigue cycles as well as the dependency of hardness increase on the applied fatigue stress value.
Acknowledgements

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