Fatigue resistance of Al-Cu-Li alloys – effect of environment

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Contents

- General introduction on Al-Cu-Li alloys → AIRWARE®
- Fatigue crack growth rate of Al-Cu-Li alloys
  - Overall behaviour very attractive
  - Al-Cu-Li alloy fit in the framework of « Poitiers », J. Petit et al.
- Fatigue performance of Al-Cu-Li alloys
  - Conventional samples
  - Technological specimens
- Specific study: effect of environment on endurance fatigue
  - With or without notch
  - Air or vacuum
- Conclusion
Airware® alloys can be used in the whole aircraft structure

Alloys in Blue designate AIRWARE® = trade mark for Constellium’s Al-Cu-Li alloys

- **Fuselage Stringers**: 2195, 2196 & 7349
- **Fuselage Skin & Webs**: 2098, 2198, 2074, 2139, 6056, 6156 & 2022
- **Upper Wing Skin**: 2195, 2075, 7449 & 7056
- **Upper Wing Skins**: 2196, 2050, 2085, 2027 & 2024
- **Lower Wing Skin**: 2196, 2050, 2085, 2027 & 2024
- **Wing Box & Inner Ribs**: 2050, 7140, 7040 & 7449
- **Wing Spars and Ribs**: 2050, 7140 & 7040
- **Wing Box & Inner Ribs**: 2050, 7140, 7040 & 7449
- **Floor Beams, Seat Tracks**: 2196
- **Main Frames, Fittings & Structures**: 2098, 2198, 2050, 2139, 6x56, 2022, 2027, 7449 & 7040
- **Hi-temp applications**: 2050, 2139 & 2xxx-HT
- **Upper & Lower Wing stringers**: 2195, 2196, 2296, 2076, 2075, 7449 & 2027

Constellium
2050 industrially applied for thick structures

A350 ribs is a key market
2198 damage tolerance → high performance fuselage

2198 T8 = alloy of C-series fuselage

Longitudinal crack length (in)

2024 HDT = A380 generation alloy
2198 T8

Initial crack (2a0)
frames

Number of flights
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Method: fatigue crack propagation in wing panels

Long range spectrum
Lower wing Al-Cu-Li alloys performing better than A380 generation alloys (2027, 2024HDT > 2024)

Gain de densité de 5 – 6%
For high strength top wing alloys, FCG under spectrum is improved by a factor 2

- All alloys have similar yield stress
FCG in metals can be described with 4 basic regimes

- FCG curves for different Al alloys and other metals (steel, Ti) can be reduced to master curves (e.g., stage II)
- Effective stress intensity factor (divided by E) is the main parameter

Water adsorption controlled regime
Hydrogen assisted regime
Intrinsic stage II
Pseudo – stage I

The 4 regimes positioning apply to AIRWARE®

- In $\Delta K_{\text{eff}}$ plots, all 3 alloys (sheet, plate, low and higher Li contents) behave similarly.
- Environment effect amounts to x100 at $\Delta K_{\text{eff}} = 3$ MPa.m$^{1/2}$.
- No environment effect at $\Delta K_{\text{eff}} > 15$ MPa.m$^{1/2}$.

[S. Richard 2011]
Pseudo-stage I observed under vacuum

- Crystallographic fracture surface at $\Delta K_{\text{eff}} < 7 \text{ MPa.m}^{1/2}$

![Image of crystallographic fracture surface]

- Stage II assisted by water adsorption
- Intrinsic stage II
- $H_2$ assisted propagation
- Pseudo stage I

Graph showing da/dN (m/cycle) vs. $\Delta K_{\text{eff}}/E$ (MPa.m$^{1/2}$) for various conditions:
- $R = 0.1$ Lab air and vacuum
- 2050 T8
- 2198-T851
- 2196-T851
- 2050-T84
- 2198-T851
- 2196-T851

[S. Richard 2011]
H$_2$ assisted fracture → chevrons + smooth zones

- Chevrons associated to cracking of {111} planes

![Chevrons associated to cracking of {111} planes](image)

R= 0.1 Lab air and vacuum

stage II assisted by water adsorption

intrinsic stage II

stage II assisted by water adsorption

H$_2$ assisted propagation

pseudo stage I

[S. Richard 2011]
Closure does not fully explain R effect

$R = 0.7 \rightarrow H_2O$ can access crack tip
An exposure based model fits with the data
The exposure based model introduced in PREFFAS allows predicting overload effect.
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Open hole fatigue: 2050 > 7050 or 7010

In many studies, 2050 shown to have better resistance than 7000 alloys
AIRWARE® alloys have 2 times longer fatigue life compared to 7xxx alloys in a low load transfer assembly fatigue configuration.

- Full surface preparation included before riveted assembly

**Low Load Transfer fatigue testing: Constant Amplitude**

AIRWARE® products have increased lifetime compared to 7xxx alloys.
Low Load Transfer fatigue testing: Variable Amplitude

AIRWARE® products have increased lifetime compared to 7xxx alloys

AIRWARE® alloys have 2 times longer fatigue life compared to 7xxx alloys: This gain is confirmed for Chromium free surface treatment

Specimen preparation: Ardrox + TSA

under spectrum LLT trials, with anti-buckling system spectrum: A318 (inverted, modified)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Number of Spectrums</th>
</tr>
</thead>
<tbody>
<tr>
<td>7056-T79 (x2)</td>
<td></td>
</tr>
<tr>
<td>7056-T79 (x2)</td>
<td></td>
</tr>
<tr>
<td>2195-T8</td>
<td>20</td>
</tr>
<tr>
<td>2195-T8</td>
<td>30</td>
</tr>
<tr>
<td>2195-T8</td>
<td>40</td>
</tr>
</tbody>
</table>

sulfochromic + CAA  
ardrox + TSA
High Load Transfer fatigue testing

AIRWARE® 2050 has typical 2xxx alloys type behaviour

AIRWARE® 2050 has a high fatigue performance in an assembled test configuration including the full surface preparation process route.

- Specimens preparation:
  - Shot peening
  - Pickling + Chromic Acid Anodizing
  - Coating with primer
  - Titanium rivet

![Graph showing fatigue performance](image)

![Diagram of test configuration](image)
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Tests selected to identify intrinsic behaviour

- Sample with and without a small slot at notch root
  - $K_t=2.15$
  - $R=0.5 \rightarrow$ no closure

- Vacuum ($<2.10^{-5}$ mBar), air at $f=0.3$ Hz, 15 Hz and 50 Hz
### Materials investigated

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Zn</th>
<th>Ti</th>
<th>Zr</th>
<th>Ag</th>
<th>Li</th>
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</thead>
<tbody>
<tr>
<td>2050</td>
<td>0.08</td>
<td>0.10</td>
<td>3.2-3.9</td>
<td>0.20-0.50</td>
<td>0.20-0.6</td>
<td>-</td>
<td>0.10</td>
<td>0.06-0.14</td>
<td>0.20-0.7</td>
<td>0.7-1.3</td>
</tr>
<tr>
<td>7010</td>
<td>0.12</td>
<td>0.15</td>
<td>1.5-2.0</td>
<td>-</td>
<td>2.1-2.6</td>
<td>5.6-6.7</td>
<td>0.06</td>
<td>0.10-0.16</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2024</td>
<td>0.50</td>
<td>0.50</td>
<td>3.8-4.9</td>
<td>0.30-0.9</td>
<td>1.2-1.8</td>
<td>-</td>
<td>0.15</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

2050 T8 90 mm  7010 T74 110 mm  2024 T3 30 mm
**2050: less constituents > 7 microns than 7010**

![Graph showing the comparison of Nb particles/mm² between 2050, 7010, and 2024 samples across different Dcircle (µm) values.](image-url)
Air, no slot: 2050 ~ 2024 > 7010

- No frequency effect

![Graph showing results for Air - no slot - 225 MPa with test frequencies of 2024 T351, 2050 T851, and 7010 T7451.](image)
Air, with the slot: 2024 > 2050 > 7010

Air - with 0.3 mm slot - 150 MPa

No frequency effect

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Constellium
Vacuum, no slot: smaller difference between alloys

- No frequency effect

![Graph showing number of cycles to failure for different alloys under vacuum with and without slots.]
Most initiation occurs on constituent particles for 7050 (similar to 7010) and 2050

- Analysis of crack initiation by FEG-SEM (after failure)
- Detection of the origin of fatigue failure
- in most cases: presence of insoluble constituent particle

alloy 7050, 150MPa, 105986 cycles
Al$_7$Cu$_2$Fe

alloy 2050, 220MPa, 32000 cycles (Al, Cu, Fe, Mn) particle
Some initiation occurs on slip bands, for 2050-T8 only

- Analysis of crack initiation by FEG-SEM (after failure)
  - At low stress level:
    - No constituent particle
    - Slip bands are present

Alloy 2050, 180MPa, 327960 cycles
Initiation on slip bands corresponds to low stress level and high fatigue life

- FEG-SEM of fatigue initiation
  - Initiation on slip bands obtained only for 2050, for stress levels $\leq 200$MPa
  - The fatigue life is higher when initiation occurs on slip bands compared to initiation on constituent particles
Inter-striation distance is higher for 7050 than for 2050

- Measure of inter-striation by FEG-SEM on failed samples at 1mm from the hole
- 1 striation = 1 cycle
Striation distance is consistent with surface crack growth rate (→ slower rate for 2050)

- da/dN obtained by:
  - Measurement of small cracks by microscopy on the surface
  - Inter-striation distance on fractographs in the bulk

- For both methods:
  - da/dN (2050)<da/dN (7050)

Note: presentation as a function of a rather than ΔK avoids theoretical issues with K definition of small cracks in open hole specimens
2050 performance: slower FCGR, (smaller constituents)

Initiation lives similar in vacuum

Propagation faster in 7010 + larger particles

Propagation faster in 7010

FCGR difference even larger in vacuum
Conclusion

- Al-Cu-Li alloys offer can fulfill the requirements on the whole aircraft

- Very high strength, higher than 7000 can be combined with 2000 type fatigue and damage tolerance properties

- Some very high damage tolerance versions show better DT than best conventional

- The effect of environment is significant and needed to understand the propagation behaviour

- Better fatigue properties than 7000 are mainly due to FCG improvement