Prove di fatica a flessione di ingranaggi cementati per elicotteri
(Bending Fatigue Tests of Helicopter Case Carburized Gears: Influence of Material, Design and Manufacturing Parameters)

Giuseppe GASPARINI, Ugo MARIANI – AgustaWestland
Carlo GORLA, Mauro FILIPPINI, Francesco ROSA – Politecnico di Milano
Abstract

• STF (Single Tooth Fatigue) Tests on Aerospace Gears
• Test Scheme and Test Rig Design
• 4 Test Groups: material, tooth root, grinding method
• Comparative tests up to 10 million cycles
• Extended tests up to 100 million cycles for one test group
• Ultimate Load Test
• S-N Shape Curves
• Conclusions and Future Developments
Introduction

- Increasing requirements of safety, reliability, performances: increasing tooth bending loads

- Influence of several aspects: design, manufacturing, material, cleanliness, case depth, residual stresses, etc.

- Loads at very high cycles ranges and short duration overloads: appropriate S-N curves

- Precise knowledge of allowable stresses to introduce in rating formulas

- Limitations of Rating Standards
Bending Fatigue Tests

- **STF vs. Rolling Tests:**
  - Different $R$ (0.1 vs 0.0)
  - Statistical aspects: different number of teeth loaded

- **STF tests:**
  - Gear Blank supported, e.g. according to SAE J1619 (more typical in US)
  - Gear Blank not supported, thanks to the properties of Wildhaber Span (more typical in EU)
AW – POLIMI STF Test Rig

- Specifically designed for the present research program
- Suited for both testing schemes, by changing the length of the left anvil
- Present tests performed with blank not supported
- Mechanical Resonance 60 kN testing machine
Gear data and test groups

Main Gear Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Teeth</td>
<td></td>
<td>32</td>
</tr>
<tr>
<td>Normal Module</td>
<td>mm</td>
<td>3.773</td>
</tr>
<tr>
<td>Helix Angle</td>
<td>°</td>
<td>0.0</td>
</tr>
<tr>
<td>Normal Pressure Angle</td>
<td>°</td>
<td>22.5</td>
</tr>
<tr>
<td>Transversal Pressure Angle</td>
<td>°</td>
<td>22.5</td>
</tr>
<tr>
<td>Transversal Module</td>
<td>mm</td>
<td>3.773</td>
</tr>
<tr>
<td>Working Pitch Diameter</td>
<td>mm</td>
<td>120.74</td>
</tr>
<tr>
<td>Base Diameter</td>
<td>mm</td>
<td>111.55</td>
</tr>
<tr>
<td>Effective Face Width</td>
<td>mm</td>
<td>15.0</td>
</tr>
<tr>
<td>Tip Diameter</td>
<td>mm</td>
<td>130.0</td>
</tr>
</tbody>
</table>

Test Groups

<table>
<thead>
<tr>
<th>Test Group Number</th>
<th>Material</th>
<th>Manufacturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>451</td>
<td>VIM-VAR 9310</td>
<td>Ground fillet, shotpeened</td>
</tr>
<tr>
<td>551</td>
<td>VIM-VAR 9310</td>
<td>Unground fillet, shotpeened</td>
</tr>
<tr>
<td>651</td>
<td>VAR 9310</td>
<td>Ground fillet, shotpeened</td>
</tr>
<tr>
<td>751</td>
<td>VIM-VAR EX 53</td>
<td>Ground fillet, shotpeened</td>
</tr>
</tbody>
</table>

Phase 1: tests with runout at 10 million cycles on all the test groups
Phase 2: tests with runout at 100 million cycles on test group 451
Test loads and tooth root stresses

ANSI/AGMA 2101-D04

\[ \sigma_F = \frac{F_t}{b \cdot m_t} \cdot \frac{1}{Y_j} \]

### FEM

<table>
<thead>
<tr>
<th>Test group</th>
<th>Fillet geometry</th>
<th>Load [kN]</th>
<th>FEM stress [MPa]</th>
<th>Strain gauge stress [MPa]</th>
<th>AGMA 2101-D04 bending stress [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>451, 651, 751</td>
<td>Ground</td>
<td>10</td>
<td>421.9</td>
<td>442.8</td>
<td>382.2</td>
</tr>
<tr>
<td>551</td>
<td>Unground</td>
<td>10</td>
<td>417.6</td>
<td>427.3</td>
<td>361.6</td>
</tr>
</tbody>
</table>
AW rating practice is based on the use of continuous curves of the family:

\[
\frac{S}{S_L} = H + A \cdot (N + C)^B
\]

- Various curves, named GEAR XX and corresponding to different values of the constants, both from AW experience and from other sources have been considered.

- Two of them have proved to best fit test data:

  GEAR 05: constants from previous AW practice
  GEAR 06: constants calculated by best fitting the present data
F – N diagram with test points, GEAR 05 and GEAR 06 (phase two data included)
F – N diagram with test points, GEAR 05 and GEAR 06

```
Number of cycles
0 1.00E+00 1.00E+01 1.00E+02 1.00E+03 1.00E+04 1.00E+05 1.00E+06 1.00E+07 1.00E+08 1.00E+09

F [N]
0 2.00E+00 4.00E+00 6.00E+00 8.00E+00 1.00E+01 1.00E+02 1.00E+03 1.00E+04 1.00E+05 1.00E+06

Test  GEAR 06  GEAR 05
```

Results 551
F – N diagram with test points, GEAR 05 and GEAR 06
F – N diagram with test points, GEAR 05 and GEAR 06
Comparison

S-N curve
GEAR 05

<table>
<thead>
<tr>
<th>Test group</th>
<th>451 1&lt;sup&gt;st&lt;/sup&gt; phase</th>
<th>451 1&lt;sup&gt;st&lt;/sup&gt; + 2&lt;sup&gt;nd&lt;/sup&gt;</th>
<th>551</th>
<th>651</th>
<th>751</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatigue Limit [N]</td>
<td>40,281</td>
<td>39,928</td>
<td>35,758</td>
<td>36,989</td>
<td>40,819</td>
</tr>
<tr>
<td>Fatigue Limit [MPa]</td>
<td>1,540</td>
<td>1,526</td>
<td>1,293</td>
<td>1,414</td>
<td>1,560</td>
</tr>
</tbody>
</table>
Comparison

S-N curve
GEAR 06
Additional activities: ultimate load tests

Ultimate load/Fatigue limit ratio

Obtained range: 1.93 to 2.17

Consistent with the maximum values of $Y_N$ given by standards for case carburized gears

ISO = 2.5
AGMA = 2.7
Additional activities: crack nucleation and propagation

Failure surface shape:
typical of case carburized 9310

Nucleation corresponding to a non homogeneity of the material

Nucleation without a defect or inclusion

Crack growth marks
Conclusions

• The extensive campaign has given precise information on fatigue limits of the four tests groups, both in absolute and relative terms.

• Analysis of the results with different shape curves

• Phase 1: tests up to 10 million cycles, 102 gear tooth specimens, 434 million cycles,

• Phase 2: tests up to 100 million cycles, 8 specimens, 734 million cycles

• Very high cycle tests confirm the estimations done on the basis of the shorter ones.

• The test procedure developed has now become the standardized approach at AgustaWestland to evaluate, compare and qualify new materials, new processes, new designs
Current and future developments

- The test program is continuing with tests on nitriding gears.

- Tests in the low cycle range on carburised case hardened gears with an hydraulic testing machine both under constant and variable amplitude loading.

- In order to improve the transferring of test data to transmission design, planned some bending fatigue rolling tests on a back-to-back rig.