Correlation of Gear Surface Fatigue Lives to Lambda Ratio (Specific Film Thickness)

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Outline

• Background / motivations
• Review of 3 NASA gear fatigue studies
• Methods to combine data from the 3 studies
• Comparison of NASA gear life data to STLE rolling bearing life factor and AGMA stress cycle factor
Concepts

“specific film thickness” or “lambda ratio”

\[ \lambda = \frac{EHL \text{ film thickness}}{\text{composite surface roughness}} \]

includes

✓ subsurface initiated spalling
✓ surface- or near-surface initiated pitting

does not include

✗ micropitting
✗ wear (mild, abrasive, adhesive)
✗ scoring or scuffing

“surface fatigue”
The correlation of lambda ratio and bearing surface fatigue has been studied for ~ 50 years. For bearings, the correlation has been quantified as an STLE Life Factor. There has been speculation that lambda ratio has an even stronger influence on life for gears than for bearings. NASA has completed several relevant studies using gears, but the data has not been combined into a unified dataset. In this study, the data will be combined and results will be compared to the guidance provided by STLE for bearings and by AGMA for gears.


Townsend completed additional 50 tests as follow-on work to study #1, but he did not report the data in open literature.

The detailed lab records and tested gears are still available, and the data were included in the present study.

258 tests in total
NASA Spur Gear Rigs
NASA Spur Gear Rigs
Gear Geometry and Test Conditions

- case-carburized ; ground (some superfinished)
- hardness Rc 58-60
- AGMA class 12
- 8 pitch (3.2 mm module)
- 6.4 mm face width
- 15 µm tip relief
- zero lead crowning
- 10,000 rpm (46 m/s pitch-line velocity)
- 72 Nm torque
- ~ 1.7 GPa Hertz stress (pitch-point)
- oil temperature 74 °C (outlet)
- break-in for 5x10^5 cycles ; 15 Nm torque
Compiling the data to correlate “lambda ratio” to “surface fatigue life”

1. surface roughness
2. film thickness
3. surface fatigue life
Test Gears – 7 “sets” from 5 batches

<table>
<thead>
<tr>
<th>study</th>
<th>material</th>
<th>manufacturing batch ID</th>
<th>profile finish method</th>
<th>roughness (Rq, mm)</th>
<th>roughness (Rq, min)</th>
</tr>
</thead>
<tbody>
<tr>
<td># 1</td>
<td>CVM AISI 9310</td>
<td>set 1</td>
<td>ground</td>
<td>0.55</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>set 2</td>
<td>ground</td>
<td>0.31</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>set 3</td>
<td>ground</td>
<td>0.59</td>
<td>23</td>
</tr>
<tr>
<td># 2</td>
<td>AM-VAR AISI 9310</td>
<td>set 4</td>
<td>ground</td>
<td>0.48 *</td>
<td>19 *</td>
</tr>
<tr>
<td></td>
<td></td>
<td>set 4a</td>
<td>superfinished</td>
<td>0.09 *</td>
<td>3.5 *</td>
</tr>
<tr>
<td># 3</td>
<td>VIM-VAR AMS 6308B</td>
<td>set 5</td>
<td>ground</td>
<td>0.42 *</td>
<td>11 *</td>
</tr>
<tr>
<td></td>
<td></td>
<td>set 5a</td>
<td>superfinished</td>
<td>0.11 *</td>
<td>4.5 *</td>
</tr>
</tbody>
</table>

Notes:
1. Roughness measured by stylus profilometer; 2 μm radius tip; ISO Gaussian filter; 0.8 mm cutoff
2. Starred (*) values in table are calculated from measured and reported Ra parameters using \((Rq = \sqrt{(\pi/2)} \times Ra)\)
3. Townsend and Shimksii had used specification’s max. Rq values, rather than measures values, to estimate lambda ratio
Measured Surface Roughness (gears from study #1)

Note: aspect ratio of plot is scaled as X:Y = 100:1
Measured Surface Roughness
(gears from study #2)
“Modified” lambda ratio

- Rq roughness values were adjusted to account for the width of the Hertz contact
- all measured roughness of this study was done using Gaussian filter with 0.8 mm cutoff
- the Hertz contact width was 0.47 mm
- adjustment was made following the guidance of Moyer and Bahney (35\textsuperscript{th} STLE/ASME Tribology Conf, 1989)

\[
Rq_{eff} = Rq_{0.8\text{mm}} \times \sqrt{(A/0.8)} \quad \text{and} \quad A = 0.47
\]
EHL film thickness

central film thickness was calculated using the Dowson-Higginson formula for line-contacts

\[ H \propto W^{-0.13} G^{0.6} U^{0.7} \]

all terms are dimensionless

- \( H \) - normalized film thickness
- \( W \) – load parameter is independent of the oil properties
- \( G \) – material parameter \( \propto \) pressure viscosity coefficient
- \( U \) – speed parameter \( \propto \) absolute viscosity

oil properties were taken at average of oil line and oil drain temperatures
### EHL film thickness

<table>
<thead>
<tr>
<th>dataset</th>
<th>lubricant description</th>
<th>specification</th>
<th>viscosity at 95—100 °C (cSt)</th>
<th>film thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>polyolester</td>
<td>MIL-L-7808</td>
<td>3.2</td>
<td>0.28</td>
</tr>
<tr>
<td>2</td>
<td>polyolester</td>
<td>none *</td>
<td>4.3</td>
<td>0.40</td>
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<tr>
<td>3</td>
<td>polyolester</td>
<td>MIL-L-23699</td>
<td>5.2</td>
<td>0.48</td>
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<tr>
<td>4</td>
<td>polyolester</td>
<td>DOD-L-85734</td>
<td>5.2</td>
<td>0.51</td>
</tr>
<tr>
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<td>polyolester</td>
<td>DOD-L-85734</td>
<td>5.4</td>
<td>0.51</td>
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<tr>
<td>6</td>
<td>polyolester</td>
<td>MIL-L-23699</td>
<td>5.4</td>
<td>0.52</td>
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<td>polyalkylene-glycol</td>
<td>DERD 2487</td>
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<td>8</td>
<td>polyolester</td>
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<td>9</td>
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<td>13</td>
<td>synthetic parrafinic</td>
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<td>synthetic parrafinic</td>
<td>&quot;NASA stnd&quot;</td>
<td>5.7</td>
<td>0.50</td>
</tr>
</tbody>
</table>

* two lubricants were basestocks without additives

Resulting lambda ratio range was 0.66 – 7.4
Surface Fatigue Lives

- surface pits were detected by rise of vibration
- a pit on any one tooth greater than 0.75 mm dimension declared as test completed
- tests completing 300 million revolutions (3 weeks) without pitting were suspended (runout)
- 2-parameter Weibull distributions determined using median rank regression method
- L10 lives from the regression solutions were used for correlation to lambda ratio
- sample sizes ranged from 10 - 30, avg. was 18
- Weibull shape (slope) ranged from 1.0 – 2.6
Surface Fatigue Lives

**L10 lives adjusted to account for different facewidths in contact** $L_{10} \propto \text{load}^{-4.2}$

- one adjustment number for each dataset per microscope inspections
- datasets 11 and 12 were further adjusted using a material factor of 2.0 (AM-VAR melt circa 1975 vs. VIM-VAR melt circa 2000 for dataset 13-14)

### Typical Weibull Plot

![Typical Weibull Plot](image)

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Weibull L10 $(10^6 \text{ cycles})$</th>
<th>Contact width $(\text{mm})$</th>
<th>Load intensity $(\text{N/mm})$</th>
<th>Relative load</th>
<th>Adjusted lives</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.1</td>
<td>2.65</td>
<td>657</td>
<td>1.13</td>
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<td>2.65</td>
<td>657</td>
<td>1.13</td>
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<td>4</td>
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<td>2.95</td>
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<td>75</td>
<td>3.00</td>
<td>580</td>
<td>1.00</td>
<td>75</td>
</tr>
</tbody>
</table>
correlation results

study #1  (ground gears – 10 oils)
correlation results

study #1  (ground gears – 10 oils)
study #2  (1 set ground, 1 set superfinished)
correlation results

study #1 (ground gears – 10 oils)
study #2 (1 set ground, 1 set superfinished)
study #3 (1 set ground, 1 set superfinished)
Guidance From STLE SP-34, Life Factor for Rolling Bearings

![Graph showing life factor as a function of lubricant film parameter](image)
Comparison of STLE Life Factor for Rolling Bearings to NASA Rig Gear Life Data

![Graph showing the comparison of STLE life factor for rolling bearings to NASA rig gear life data.](image)
Guidance From AGMA Gearing Standard,
Influence of Lubrication on Gear Pitting Rating

<table>
<thead>
<tr>
<th>Regime</th>
<th>&quot;Full EHL&quot;</th>
<th>&quot;Mixed EHL&quot;</th>
<th>&quot;Boundary Lube&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transitions (lambda ratio)</td>
<td>1.0</td>
<td>0.4</td>
<td></td>
</tr>
</tbody>
</table>
Guidance From AGMA Gearing Standard,
Influence of Lubrication on Gear Pitting Rating

NASA Gear Rig – lambda ratio correlation

stress factor

surface fatigue life (cycles)

region of interest for rotorcraft
Summary

1. Results from 258 surface fatigue tests using the NASA gear rigs were collected to study the correlation of lambda ratio to life
2. Lambda ratios ranged from 0.66 to 7.4
3. L10 gear lives ranges from 5 to 100 million cycles
4. The correlation matches well with the trends of recommended STLE life factors for bearings and AGMA 925-A03 guidance