Microscopic and Spectroscopic Characterization of Gear Tooth Damage from a Loss-of-Lubrication Event

Dr. Stephen Berkebile, U.S. Army Research Laboratory
Dr. Robert F. Handschuh, NASA Glenn Research Center
MAJ Edwin A. Churchill II, U.S. Army Research Laboratory
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- NASA Rotary Wing

Special thanks to …

- Space Power Branch (NASA Glenn)
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- Swagelok Center for Surface Analysis of Materials (CWRU)
Oil starvation
- Can occur due to …
  - Loss of lubrication
  - Higher speeds and loads
- Results in …
  - Film breakdown / Contact
  - High friction
  - Heat generation
  - Wear
  - Failure

Autorotation to landing not always an option (location, seizure)

U.S. Army rotorcraft qualification requires operation for 30 minutes after loss of primary lubrication system (ADS-50-PRF)

Future challenge
- Move beyond auxiliary and emergency lube systems
- Develop materials and lubricants to meet and extend oil-starved lifetime
- Understand chemical and physical processes during oil starvation!!!
• NASA Spur Gear Test Rig

• Post-analysis of gear teeth
  - Geometry and Morphology (Optical microscope, Profilometry, SEM)
  - Chemical analysis (SEM/EDS, XPS, Raman)
  - Depth profiling (AES, FIB-SEM)

• Conclusions
NASA Glenn Contact Fatigue Test Facility

- Oswald, F., NASA/TM—2004-212722;

10,000 rpm

<table>
<thead>
<tr>
<th></th>
<th>28 tooth gear</th>
<th>42 tooth gear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diametral pitch (1/in.)</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Pressure angle (deg.)</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>Pitch diameter (in.)</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Addendum (in.)</td>
<td>0.125</td>
<td>0.083</td>
</tr>
<tr>
<td>Whole depth (in.)</td>
<td>0.281</td>
<td>0.196</td>
</tr>
<tr>
<td>Chordal tooth thickness (in.)</td>
<td>0.191</td>
<td>0.128</td>
</tr>
<tr>
<td>Face width (in.)</td>
<td>0.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Handschnuh et al., NASA/TM—2011-217106
Typical run

- Break-in at lower load
- Run at full load to steady state (about two hours)
- Turn off oil supply
NASA Spur Gear Test Rig

Post-analysis of gear teeth
- Geometry and Morphology (Optical microscope, Profilometry, SEM)
- Chemical analysis (SEM/EDS, XPS, Raman)
- Depth profiling (AES, FIB-SEM)

Conclusions
Materials and Experiment

- **M50 steel gears** (typical bearing steel)
  - TEM micrograph of untreated M50 steel
  - Fe | C | Cr | Mo | V | Si
  - balance 0.8% 4% 4% 1% 0.2%

- **5 cSt turbine oil** (DOD-L-85734)
  - Typically polyol ester base
  - Chemical additives (amines, chloralkyl phosphonate, etc.)
    - Antiwear
    - Detergent
    - Corrosion inhibitors
    - Antifoaming
    - Extreme pressure

- **Stop experiment before destruction**
  - Typically will reach >550 °C
  - Stopped here at estimated 500 °C gear surface average temperature

**Thermocouple temperatures**
- Gear surfaces are higher
- Oil In
- Oil Out
- Left Gear
- Right Gear
- Out of Mesh

- **Stop - rotation**
- **lubrication off**
- **(runaway imminent)**

**Thermocouple positions and rotation**
Teeth for analysis

- Two teeth from different gear positions
  - Crowned
  - Representative of all teeth
- Loss of 5 – 10 µm along center line

Tooth from opposite gear facing #2 (not to proportion)

Handschoh et al., NASA/TM—2011-217106

Tooth #1

Profile - Center

Lead - Tip

Tooth #2

Profile - Center

Lead - Center

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Scanning Electron Microscopy

Tooth #1

1. Edge of scuff
2. End of scuff
3. Inside scuff
4. Outside scuff
What’s on the surface?

- **SEM with Energy Dispersive Spectroscopy**
  - Depth resolution/sensitivity ~3 µm

**Tooth #1**

Color density indicates concentration

steel components and oxidation

- Fe
- O
- Cr
- V
- Mo/S
- C

additive components

- P
- Na
- Ca

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What's on the surface?

- **SEM with Energy Dispersive Spectroscopy**
  - Depth resolution/sensitivity ~3 µm

- **Tooth #2**

![SEM images with elemental mapping](image)

- Fe
- O
- Mo
- C
Two areas, four general features

- Edge outside scuff
  - Additive-modified surface
    - Only on edges and fillet
- Inside scuff
  - Fresh steel
    - Elongated in direction of motion
  - Oxide scales
    - Especially at tip, but spread inwards
  - Carbon
    - Especially at pitch line, but also elsewhere
**X-ray Photoemission Spectroscopy**
- First few nm of material
- 0.1 at. % sensitivity, ~1 % accuracy

**Tooth #2**

<table>
<thead>
<tr>
<th>Atomic %</th>
<th>Oxide scale (1)</th>
<th>Fresh steel (2)</th>
<th>Carbon (3)</th>
<th>Edge outside scuff (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>38.4</td>
<td>35.4</td>
<td>6.7</td>
<td>2.1</td>
</tr>
<tr>
<td>O</td>
<td>59.2</td>
<td>56.8</td>
<td>11.5</td>
<td>43.0</td>
</tr>
<tr>
<td>C</td>
<td>2.4</td>
<td>7.2</td>
<td>80.3</td>
<td>29.8</td>
</tr>
<tr>
<td>Mo</td>
<td>0.3</td>
<td>0.1</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td></td>
<td>1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td></td>
<td>0.2</td>
<td>7.1</td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td></td>
<td></td>
<td>7.6</td>
<td></td>
</tr>
<tr>
<td>Na</td>
<td></td>
<td></td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td></td>
<td></td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>Zn, Mg, Cd</td>
<td></td>
<td></td>
<td>&lt;1.0</td>
<td></td>
</tr>
</tbody>
</table>
X-ray Photoemission Spectroscopy

Tooth #2
- No carbide

What is really on the surface? (a closer look)

- Oxide scale
- Steel
- Carbon

Intensity (arb. un.)

Binding Energy (eV)

C1s

Intensity (arb. un.)

Binding Energy (eV)

O1s

Intensity (arb. un.)

Binding Energy (eV)

Fe2p

Intensity (arb. un.)

Binding Energy (eV)

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What is really on the surface? (a closer look)

- X-ray Photoemission Spectroscopy
- Tooth #2
  - No carbide

Raman spectroscopy of Carbon Area 3:
- Not oil, but graphitic

Intensity (arb. un.)

Binding Energy (eV)

Normalized intensity, arb. un.

Raman shift, cm⁻¹

Carbon, λ=532 nm
Ref. oil, λ=532 nm
Carbon, λ=780 nm
Ref. oil, λ=780 nm

D & G bands

C-H

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How deep does it go?

Scanning Auger Electron Spectroscopy Depth Profiling

- Edge outside of scuff

![Graph showing depth profiling](image1)

![Graph showing depth profiling](image2)

Tooth #1

Tooth #2
Scanning Auger Electron Spectroscopy Depth Profiling

- Central scuff

Graphs showing atomic concentration vs. depth for different elements in Tooth #1 and Tooth #2.

Tooth #1

Tooth #2

O  Fe  C

O1  Fe3  C1  Ca1

S1  Na1  P1  Mo1

V1  Si1

Depth (nm)

Depth (nm)
Focused Ion Beam sectioning with SEM

Tooth #2

Oxide scale in scuff

Top view (optical microscope)

Cross-section

How much deeper?
Focused Ion Beam sectioning with SEM

Tooth #1

Near edge

Center of scuff

additive species + oxide (3-5 µm thick)
steel

steel and oxide mixing
NASA Spur Gear Test Rig

Post-analysis of gear teeth
- Geometry and Morphology (Optical microscope, Profilometry, SEM)
- Chemical analysis (SEM/EDS, XPS, Raman)
- Depth profiling (AES, FIB-SEM)

Conclusions
What have we learned?

- **At this point during gear failure ...**
  - Additive species diffuse into unscuffed surface
    - Not much Fe at surface
    - No oil left
    - Ca, (O, C), P, S, Na, up to 0.5 µm
    - Something in additives slows oxidation at elevated temperatures
    - Removed by scuffing
  - Oxide scales form within scuff
    - About 1 – 5 µm thick
    - Preferentially under high sliding
    - Some spall off
    - Some mix with the steel (plastic displacement)
    - Abrasion?

- **Oxidation and additive chemistry are actively affecting surface of steel during run away stage of gear failure**
Where do we go from here?

- More points along the temperature/failure curve
  - Fuller understanding of failure mechanisms
  - Identify first failure modes
  - Identify continuing failure modes

- Start considering solutions
  - Oxidation inhibitors
  - Additives
    - As main component in emergency systems
    - Subsurface reservoirs
  - What else?

- Feed information into controlled tribological simulations
Support Material
Exploration of gas evolution

Quadrupole Mass Spectrometer sampling gear box air
- Possibly interesting action is happening

- Needs better equipment
  - Speed
  - Synchronization
  - Sensitivity

- Issues with affecting tests

- Potential uses
  - Detect looming failure
  - Insight into chemistry occurring