Surface Roughness and Micropitting

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• Introduction
• Micropitting Basics
• Solution
  – Superfinishing
• How it Works
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Introduction

- Wind turbines have grown larger (1.5-6 MW)
  - Led to large, multistage gearboxes
  - Gearbox reliability has suffered
  - Many require replacement/overhaul at 5-7 years
  - Drives up the cost of ownership

(Source: NREL)
What are the issues?

- Large turbine blades create massive torque loads on the drivetrain
- Gears operate at relatively low speeds
- Operate in variable conditions
  - Temperature fluctuations
  - Standstill
  - Multiple start/stop
  - Idling
- Operate under variable loads
Current Lubrication Systems

- Lubricants are a compromise for gears, bearings and seals
  - Thick enough for gears, thin enough for bearings
  - Boundary/Mixed lubrication conditions
  - Contact fatigue
  - Plastic deformation of metal asperities
  - Particles in lubricant
- Filtration can be a challenge
  - FOD
Typical Results After Operation

- Corrosion
- Abrasion
- FOD Damage
- Micropitting
Micropitting Basics
Micropitting Basics-Tooth Mesh Sliding

- **Driver**
  - Initial contact near root
  - Rolls up
  - Sliding is away from pitchline

- **Driven**
  - Initial contact near tip
  - Rolls down
  - Sliding is towards pitchline

- **Cracks**
  - Grow opposite direction of sliding
  - Converge at pitchline

- **Hydraulic Pressure Propagation**
  - Negative sliding at dedenda accelerates crack propagation by the hydraulic-pressure-propagation mechanism proposed by Stewart Way.

(Source: Robert Errichello)
Micropitting-Surface Topography

- Micropitting attacks high points
  - Crests of undulations
  - Peaks of scallops
  - Ridges of grinding lay
  - Edges of grinding scratches
  - Shoulders of debris damage

- Micropitting locations
  - Can be found along high points
    - Asperities
  - Typically located in the dedendum
  - Appears as a “Grey Stain”

(Source: Robert Errichello)
Micropitting Basics-Failure Modes

- Major replacement cause of highly loaded case hardened gears
- Reduces gear life
- Reduces load-bearing capacity
- Can lead to macropitting
- Can lead to wear

(Source: Germanischer Lloyd)
• Wear occurs on gear flanks
  – Mostly in dedendum
    • High Sliding
  – Increases in severity with load cycles
Superfinishing

- Modifies topography
- Eliminate Micropitting
- Increases Lubricant Life and Cleanliness
- Increase Component Life
- Easy to Implement
How It Works
ISF stands for Isotropic Superfinish

A Ground Surface has directionally oriented, parallel rows of surface asperities.

An Isotropic Superfinished surface has no asperity peaks, only a non-directional surface texture.
Superfinishing-ISF®

- Chemically Accelerated Vibratory Finishing
- Reduces Surface Roughness to < 0.1 µm $R_a$
- Planarizes and Micro-Textures the Surface
- Maintains Component’s Geometry

High Quality Vibratory Equipment

High Density, Non-abrasive Media
Superfinishing Process
Surface Roughness Reduction

**Worst**

Starting Condition: Ground surface having peak and valley asperities along with a distressed layer of metal at the surface.

- $R_s$: 0.58 $\mu$m
- $R_z$: 3.5 $\mu$m

**Better**

Stage 2: Superfinished where only a few valley asperities remain on the surface.

- $R_s$: 0.13 $\mu$m
- $R_z$: 1.1 $\mu$m

**Good**

Stage 1: Partially superfinished surface where the peak asperities have been planarized.

- $R_s$: 0.30 $\mu$m
- $R_z$: 2.0 $\mu$m

**Best**

Final Condition: Superfinished surface with all asperities removed while displaying the beneficial and inherent micro-texture.

- $R_s$: 0.025 $\mu$m
- $R_z$: 0.17 $\mu$m
Planarization Mechanism
Why It Works
Quick Review of Lubrication Theory

- A low film thickness/surface roughness (λ) results in:
  - Boundary lubrication
  - Mixed lubrication
- A high (λ) completely separates two load-bearing surfaces and results in:
  - Hydrodynamic lubrication
Quick Review of Lubrication Theory

(Source: KEW Engineering, Ltd)
Suppose that two gears operating under their most severe conditions have a minimum lubricating film thickness of 100 µm.

If it is experimentally determined that when the two gears are separated by a minimum lubricating oil film of 10 µm, the gears do not micropit.

Then the Safety Factor against Micropitting is 100 µm / 10 µm = 10.
Micropitting Safety Factor in ISO TR15144

\[ S_\lambda = \frac{\lambda_{GF,\text{min}}}{\lambda_{GFP}} \]

- \( S_\lambda \) is the safety factor against micropitting
- \( \lambda_{GF,\text{min}} \) is the minimum specific lubricant film thickness
- \( \lambda_{GFP} \) is the permissible specific lubricant film thickness
Local Specific Film Thickness

\[ \lambda_{GF,Y} = \frac{h_Y}{R_a} \]

- \( \lambda_{GF,Y} \) is the local specific lubricant film thickness
- \( h_Y \) is the local lubricant film thickness.
  - This might be measured or calculated
  - Not relevant to this presentation as only considering a reduction in surface roughness (\( R_a \))
- \( R_a \) is the effective arithmetic mean roughness value

Where

\[ R_a = 0.5(R_{a1} + R_{a2}) \]

- \( R_{a1} \) = arithmetic mean roughness value of Driver
- \( R_{a2} \) = arithmetic mean roughness value of Driven
Increasing the Safety Factor

- It’s obvious then, that the Safety Factor can be increased by:
  - Increasing $\lambda_{GF,\text{min}}$, and/or
  - Decreasing $\lambda_{GFP}$

- Since $\lambda_{GF,\text{min}}$ is the minimum value of $\lambda_{GF,Y} = h_Y / R_a$

- Reducing $R_a$ will increase $\lambda_{GF,Y}$.
For typical wind turbine gears were:

- $R_a$ (Ground Surface) = 0.5 µm
- $R_a$ (Superfinished Surface) = 0.1 µm

Then it is obvious that for the same gearbox:

- $\lambda_{GF,\text{min}}$ (Superfinished Surface) = 5 $\lambda_{GF,\text{min}}$ (Ground Surface)

Conclusion:

- Superfinishing the gears to a 0.1 µm $R_a$ increases the Micropitting Safety Factor by a factor of 5
Support for Previous Conclusion

1. KISSsoft, AG refers to a chart from the presentation Tribologische Aspekte bei Zahnradgetrieben - Speziell für Fahrzeuge – Prof. Dr.-Ing. Wilfried J. Bartz, T+S Tribologie und Schmierungstechnik, Denkendorf 5. Internationales CTI Symposium

2. They adapt it to wind turbine gears

3. Conclude that there are only three remaining practical methods of improving gears to prevent micropitting:
   1. Superfinishing
   2. Change the gears macro geometry
   3. Change the gears micro geometry

Note: Once designed and in production, the only practical method is Superfinishing.
<table>
<thead>
<tr>
<th>Material, Surface</th>
<th>Action</th>
<th>Effectiveness</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce flank roughness to 1/16</td>
<td>1:2</td>
<td>See use of superfinishing gears in wind industry</td>
<td></td>
</tr>
<tr>
<td>Gears with run-in vs. without run-in</td>
<td>1:3</td>
<td>Running in of gears may be done during serial testing of gearboxes. The effectiveness may be lower for superfinished gears and gears with micro geometry modifications.</td>
<td></td>
</tr>
<tr>
<td>Case carburizing vs. Nitriding vs. Phosphating vs. Use of copper plating</td>
<td>1:2:1.4:3</td>
<td>Seems to be impractical since only case carburized gears are used for external gears in wind industry.</td>
<td></td>
</tr>
<tr>
<td>Normal vs. stainless steel</td>
<td>1:0.3</td>
<td>The use of stainless steel is limited.</td>
<td></td>
</tr>
<tr>
<td>Lubricant</td>
<td>Use of EP Additives</td>
<td>1:5</td>
<td>The use of lubricants with EP additives and other additives is considered state of the art in wind industry.</td>
</tr>
<tr>
<td>Double the viscosity</td>
<td>1:1.15</td>
<td>The viscosity of lubricants as used in the wind industry is typically v40 = 320 mm²/s</td>
<td></td>
</tr>
<tr>
<td>Gear Design</td>
<td>Change in gear macro geometry</td>
<td>1:6</td>
<td>An optimal gear design is in the responsibility of the gear designer.</td>
</tr>
<tr>
<td>Change in gear micro geometry</td>
<td>1:2</td>
<td>Suitable modifications of the gear geometry should be applied by the gear designer.</td>
<td></td>
</tr>
<tr>
<td>Spur vs. helical gears</td>
<td>1:0.75</td>
<td>Typically, helical gears are used due to the high requirements in terms of noise levels.</td>
<td></td>
</tr>
<tr>
<td>Operation</td>
<td>High vs. low circumferential speeds</td>
<td>1:8</td>
<td>Circumferential speed is determined by the rotor speed and gear size and is hence difficult to change.</td>
</tr>
</tbody>
</table>

Green: relevant and may be applied by gear designer  
Yellow: partly relevant as already state of the art in wind industry  
Red: not applicable in wind industry
KISSsoft, AG confirms Superfinishing to a 0.1 µm $R_a$ increases the Micropitting Safety Factor five times

- **Ground Flanks**
  - $R_z$: 4.5 µm
  - $R_a$: 0.45 µm

- **Superfinish Flanks**
  - $R_z$: 1.0 µm
  - $R_a$: 0.10 µm
Micropitting Test Results
Part I reported results from the FZG Brief Test of Gray Staining (BTGS)

- Low micropitting resistance oil - FVA2 +LZ677A
- Standard FZG-C gearsets
- Baseline: $R_a = 0.5 \pm 0.1$ micron (ground)
- Superfinished: $R_a = 0.1$ micron
- Failure definition: 7.5 micron mean max profile deviation
- Testing Location: Technical University of Munich
The Effect of Superfinishing on Gear Micropitting
Part I-STLE 2008

- Superfinished gears did not fail.
- Superfinished Results-LS-9
  - < 3.5 µm
- Baseline Results-LS9
  - 9.7 and 10.3 µm
Part II – Test Specifics

• Micropitting test per FVA-Information-sheet 54/I-IV

• Lubricant
  – Mineral oil
  – ISO viscosity class 200
  – Additive to reduce the micropitting carrying capacity
  – Injected at 60 °C

• Baseline: Standard-FZG-C-gear set
  – 0.5 µm $R_a$

• Superfinished: Standard-FZG-C-gears
  – Nominal 0.1µm $R_a$

• Pitch line velocity: 8.3 m/s

• Test 1: Load Stage Test

• Test 2: Load Stage and Endurance

• Test Location: Ruhr University Bochum
Test Run 1 was the Load Stage Test in which the loading was increased every 16 hours starting with load stage 5 and ending after load stage 10.

Test Run 2 consisted of a completed Load Stage Test followed by an Endurance Test. The Endurance Test starts with an 80-hour cycle at load stage 8, followed by five 80-hour cycles at load stage 10.
Load Stage and Endurance Test

Baseline Tooth Flanks
Micropitting = 79 %
Load Stage and Endurance Test

A thin gray mark is not micropitting; it was due to a lack of tip relief.

Superfinished tooth flanks

Micropitting mark is **not** micropitting; it was due to a lack of tip relief.
REM, The ISF Process, and the Wind Turbine Market
A Brief History of REM Superfinishing

Technology developed in the early 1980’s for decorative finishes.

Engineered Surface Finishing started in the late 1980’s.

Isotropic Superfinish (ISF®) Processing of gears started in the early 1990’s.

ISF® Processing of large gears and extremely small gears started in the early 2000’s.

ISF® Process is applied to gear refurbishment in mid 2000’s.
2003
• Winergy AG agrees to test ISF®
  – Winergy receives exclusive utilization of ISF® in Wind Energy Market on Gearboxes

2007
• REM begins refurbishment of used gearboxes

2010
• Winergy and REM amend exclusive agreement
  – REM provides ISF® Process to any Wind Turbine Gearbox
History in Wind Energy

- New Gearboxes to date
  - >9,000 MW class

- Refurbished Gearboxes
  - >200 MW and KW class
Conclusions
Conclusions

- Superfinishing reduces $R_a$ and modifies surface topography to a planarized condition

- Superfinishing eliminates micropitting

- Superfinishing wind turbine gears to 0.1 µm $R_a$ increases the Micropitting Safety Factor by five
  - The following calculations support the claim:
    - ISO TR 15144-1
    - KISSsoft, AG papers
Conclusions

• FZG-C gears superfinished to 0.1 µm $R_a$

  – Did not micropit during a FZG Brief Test of Gray Staining (BTGS) using Low micropitting resistance oil

  – Did not micropit during 2 independent FZG load stage tests at LS10

  – Did not micopit during an endurance test consisting of 5 80 hr tests at LS10.
References

- Morphology of Micropitting, R.L. Errichello, AGMA FTM, 2011, 11FTM17
- Tribologische Aspekte bei Zahnradgetrieben - Speziell für Fahrzeuge, Prof. Dr.-Ing. Wilfried J. Bartz, T+S Tribologie und Schmierungstechnik, Denkendorf 5. Internationales CTI Symposium
- Un software per il calcolo a micropitting, Stefan Beermann e Ulrich Kissling, KISSsoft AG Hanspeter Dinner, EES KISSsoft GmbH, Organi di trasmissione - settembre 2010
- The Effect of Superfinishing on Gear Micropitting (Part I), L. Winkelmann, P. B. King, M. Bell, O. Elsaeed, STLE Annual Meeting, May, 2008.
- The Effect of Superfinishing on Gear Micropitting (Part II), L. Winkelmann, M. Bell, O. Elsaeed, AGMA FTM, 2008, 08FTM10.
Additional Questions?

www.remchem.com