Wind Turbine Lubrication
Comparison of Power Sources

• Huge single footprint asset
• Redundant equipment with easy access
• Multiple sensors and performance monitors
• On-site Manned Control Room
• On-site Maintenance Crew

• Small footprint assets scattered over a wide, isolated area
• No redundancy equipment in nacelle: 80m + above ground
• Few if any sensors or monitors
• No centralized monitoring
• Off-site Maintenance Crew
Wind Turbine Reliability

>1MW

Unscheduled Maintenance

Six Times More Than Planned Scheduled Maintenance

Source: Sandia National Labs, CREW Event and SCADA data source: ORAP for Wind (R)
Wind Turbine Size Continues to Grow

1.5Mw to 2.5Mw
As Wind Turbine Size Increases Reliability Decreases

Reliability of wind turbines
It is clear that the failure rates of the 500/600 kW class installed, have almost continually declined in the first operational years.

However, the group of mega-watt Wind Turbines show a significantly higher failure rate, which also declines by increasing age.

Source: ISET Hahn, Durstewitz & Rohrig
1.5 MW Wind Turbine Parts Cost by System

Based on a 60MW Project Size Variable Speed, Electric Pitch

Source: NREL National Resource Energy Laboratory
Gear Box
Lubrication Fundamentals
Typical Wind Turbine Gear Box

- Compact design due to weight restrictions
- High load handling capability
- Case hardened gears
Understanding Stress Loads in the Gear Box
Photo-elastic analysis of two gear teeth in contact shows that there are three types of high stress on the teeth:

- **At A** we see Tensile Stress and at **B** we see Compressive Stress due to bending of the tooth.
- The bending stress is cyclic as it occurs once per revolution of the gear and will, thus, lead to a potential fatigue failure (like continual bending a coat hanger).
Gear Teeth Breakage
Caused by Tensile and Compressive Stress

Fractured tooth
Cracks

Typical tooth breakage from fatigue cracks starting at the root of a tooth and arising from bending loads from the driving torque

Courtesy: Neal Consulting Engineers
Gear Teeth Breakage

- Gear Teeth breakage not associated with lubrication
- Continuous shock overloading
- Uneven load distribution across face width increases the risk of breakage
- Surface hardness and Core hardness differential may lead to embrittlement
Contact Stress at the Rolling Pitch Line of the Gears Elasto-Hydrodynamic Lubrication Area

• At C we have a Contact Stress situation as the two, approximately cylindrical surfaces roll and slide on each other during every tooth contact. This contact stress may lead to a surface pitting fatigue along the gear tooth pitch line.
Pitting - Hertzian Fatigue

• Pitting occurs when a fatigue crack initiates either at the surface of a gear tooth or a small depth below the surface.
• Small particles are removed from the surface of the tooth because of the high contact forces.
• Pitting is actually the metal fatigue failure of the tooth surface.
• Surface irregularities caused by pitting lead to **loss of oil film** in the contact zone and eventual failure.
Macropitting or Destructive Pitting
Spalling
When pits coalesce or grow together

*Spalling* resembles destructive pitting, except that the pits are much larger, quite shallow, and irregularly shaped. The edges of the pits break away rapidly, forming large, irregular voids that may join together. Spalling is caused by excessively high contact stress levels.
Gear Spalling

Spalling is a term used to describe when a large area of the gear tooth breaks away, caused by:

- High contact stresses associated with proud areas of the tooth surface and **loss of oil film caused by destructive pitting**
- Excessive or internal stresses (Over Loading)
- Improper heat treatment in surface-hardened gears
The Lubrication Challenge of Micropitting

Lubrication’s Role in Wind Turbine Reliability and Life
Micropitting

• Micropitting is characterized by the presence of fine surface pits and the occurrence of local plastic deformation and shallow surface cracks

• It produces significant wear of the gear surface causing loss of profile of the teeth leading to noise

• Root Cause Failure analyses show that micropitting is frequently a primary failure mode responsible for initiating other secondary failure modes such as macropitting, scuffing, bending fatigue, and spalling
Micropitting

• Gears subject to extreme loads like those found in Wind Turbines are surface hardened (carburized, nitrided, induction hardened and/or flame hardened)

• Micro-pitting, unlike macro-pitting, **usually** starts away from the mating pitch line of the gear teeth at the addendum and dedendum
Micropitting

- Micropitting occurs in smaller scale, typically 5 to <10 µm deep
- To the naked eye, the area where micropitting has occurred appears frosted, and “frosting” is a popular term of micropitting
- Spur tooth from FZG test showing micropitting damage in the root region

Photo Courtesy: Design Unit, Newcastle University
Examples of Wind Turbine Gear Surface Micropitting

Notice the “frosting” in the dedendum and addendum (below and above the pitch line of the gear)
Gear Surface Micropitting

- Frosted appearance (same as bearing micropitting)
- Can progress across the entire tooth profile
- May stop or progress to macropitting
- Associated with $\lambda$ ratios $\leq 1.0$
Gear Surface Micropitting – *Lambda Ratio*

- *Lambda ratio* is the relationship between surface roughness and lube film thickness.
- Low lambda ratio is associated with micro-pitting (*surface too rough* or *lube film too thin*)
Wind Turbine Gear Boxes Bearings Are Also Affected by Micropitting
Bearing Surface
Stress Response with Respect to Pressure

Oil Film in
Pressurized Zone
0.1 to 5 micron thickness
Wind Turbine Bearing Micropitting

• Micropitting is especially detrimental to bearing function because it **alters the geometry of rollers, raceways, or both**
  
  – The altered geometry increases internal clearance and results in **edge stresses** that ultimately cause macropitting and bearing failure.
Micropitting Leading to Catastrophic Surface Damage

Notice the overall dull (frosted) surface of the bearing caused by micropitting.

Resulting altered geometry of the bearing leads to edge stress and macropitting as well as particulate indentation damage to bearing surface.
Bearing Inner Race Micropitting

- **Frosted appearance**
  - Same as gear micropitting
- Surface covered by very fine and shallow pits
- Associated with Lambda ratios ≤ 1.0
- Severe Edge Pitting
Micropitting Leads to Geometric Stress Concentration Fatigue

- Onset of micropitting (left): two wear tracks have emerged in the center of the raceway.
- As micropitting continues, material is worn away leading to a loss of the design contact geometry in the center and increasingly higher stress concentrations at the edges of the wear track.
- Fatigue spalls initiate at these areas of high GSC and propagate to the center of the raceways.
Micropitting Increases Surface Roughness

• Full film, Elasto-hydrodynamic lubrication depends on maintaining a oil film of just .01 to 5 microns to separate surface asperities

• 10µm deep Micropitting on both gear surfaces results in a possible combined asperity gap of >20µm – which is greater than the oil film

• RESULT:
  – Boundary Lubrication or metal to metal contact
  – More loading on the tips of the asperities
  – Pitting
  – Metal Particle Contamination
In most cases, bearing wear propagates 3\textsuperscript{rd} body wear particles that lead to both bearing and gear surface destruction.
If it is Just the Lambda Ratio, Why Not Use Higher and Higher Viscosity Lubricants Until the Micropitting Problem is Solved?
Why Not Higher Viscosity Fluids?

• Pour point
• Low temperature pumpability
• Filterability
• Excessive heat generation
• Power loss
• **Presence of BOTH low and high speed gears and bearings in the same gear box**
  – A “viscosity compromise” is typically required for gearboxes with a common sump
  – Typically the operating temperature of the gear drive determines the operating viscosity of the lubricant.
Micropitting Summary

**Sliding Friction:** Sliding between gear teeth at low lambda in the addendum and dedendum areas causes tractional forces that subject asperities to shear stresses which can propagate micropitting.

**Contact Compression:** Bearing and Raceway contact at low lambda also subjects asperities to shear stresses which can propagate micropitting.
Stribeck-Hersey Curve

Effective Range for Additives

Oil Films Thicker than Metal Asperities

Coefficient of Friction

Boundary

Mixed

Hydrodynamic Elasto–hydrodynamic

Area of Micropitting Occurrence
Micropitting Prevention
Micropitting Prevention
Control Water Contamination

Many experiments have shown water in oil promotes both micropitting and macropitting.

Lubricants are susceptible to water contamination:
- Ester-based lubricants
- Mineral oils with EP or anti-wear additives are especially prone to absorbing water.
Micropitting & Macropitting Causes

**Water Contamination** in the gear oil can promote both micropitting and macropitting through:

- Loss of oil film –
  - Water interferes with the pressure-viscosity coefficient of the oil – its ability to momentarily solidify in the contact area
- Corrosive wear (rusting)
- Hydrogen embrittlement
Effect of Water Concentration on Bearing Life*

*Cantley, R., "The Effect of Water in Lubricating Oil on Bearing Fatigue Life"
Water Contamination of Lubricants

- **With water contents of about 200 ppm**, a reduction in bearing fatigue life has been measured, depending on bearing type and composition of the lubricant.
- The primary cause is **NOT** the viscosity reduction by mixing the oil with water.
- **BUT** the occasional passage of microscopic water droplets under high pressure through the lubricating zone and the resulting local lubricating film breakdown!
- The Number and the Size of the microscopic droplets increase with the amount of water – which means the Probability of water passing through the lubricating zone increases as well.
Water Contamination of Lubricants

- With **water concentrations above 300 ppm**, the tendency of oils to form residues at high temperatures, in the form of
  - Sludge
  - Varnish
- This not only accelerated the aging of the base oils, it also **causes additives to precipitate out or reduces their effectiveness**
- An increased risk of surface **CORROSION** has to be expected if there is free water in a lubricating system
Water Contamination - Emulsions

• Thickened Oil/Water Emulsions also suspend abrasive particles in lubricants and cause surface damage by indenting and scratching the metal surface, causing stress concentrations, and disrupting the lubricant film
Particles in Dirty Lubricant Causes Stress Risers in the Contact Zone

Clean Surfaces completely separated by lubricant film

Solid Contaminant Particles contained in the lubricant film

Source: Johan Luyckx
Bearing Flaking - When Micropitting and Macropitting Coalesce

**Subsurface Originated**
- (Classical theory)
- Under clean lubrication condition
  - Non-Metallic Inclusion
  - Crack
  - Flaking

**Surface Originated**
- Under contaminated lubrication condition
  - Dent
  - Crack
  - Flaking

**White Structure**
- Specific applications
  - White Structure

*Photos Courtesy of NSK Ltd.*
Contaminated Lubricant
Raceway Dent Caused by Particles

- Dent
- Stress concentration
- Crack
- Contact stress
- Flaking
Crack and Flaking Originated From Edge of Dent on Raceway Surface

Photos Courtesy of NSK Ltd.
Hydrogen Embrittlement of Bearing Material

1. Ball moving direction
2. Slip
3. Fresh surface
4. Poor oil film, local metal-to-metal contact, formation of fresh surface
5. Decomposition of lubricant causes hydrogen generation
6. Hydrogen diffuses into steel
Micropitting Prevention
Lubrication Effects – Base Fluids

Selection of basestocks and additive chemistry also affect micropitting

• Tests have shown that micropitting resistance varies from lubricant to lubricant
• Oil solidifies under the high pressure generated in Elasto-hydrodynamic lubrication
• Tractional Stress on surface asperities is limited by the shear strength of the solidified oil
• Different basestocks have differences in solidification pressures and shear strength
Micropitting Prevention
Lubrication Effects – Base Fluids

• **Polyglycols & Esters** have low shear strength with their flexible ether linkages – good lubricity.
  – Polyglycols are very hygroscopic and have poor compatibility with many seal materials and paints
  – Esters are also hygroscopic

• **Naphthenic mineral oils** are too “stiff”, with compact molecules that have a high traction coefficient
Micropitting Prevention
Lubrication Effects – Base Fluids

- **Paraffinic mineral oils** have open, elastic molecules and low traction coefficients (good lubricity)
  - Good Additive solubility
  - Poor demulsibility (compared to PAOs and Group IIIIs)
  - Mineral oils contain numerous contaminates that may cause deposits and surface corrosion (corrosive pitting) under EHL pressures and heat
Micropitting Prevention
Lubrication Effects – Base Fluids

• **Polyalphaolefins (PAOs)** have open, elastic molecules with low traction coefficients – good lubricity
  – High molecular weight PAO have extremely high VIs
  – Poor additive solubility

• **Group III** Paraffinic basestocks also have open, elastic molecules with low traction coefficients – good lubricity
  – Their additive solubility is slightly better than PAOs
Micropitting Prevention
Possible Base Fluid Solutions

- **Combinations** of low and high molecular weight PAOs that improve additive solubility
- **Novel Base Fluids** such as alkylated naphthalenes or oil soluble polyalkyleneglycols (PAGs) mixed with PAO or Group III
- **Novel Polymer Chemistries** with PAO or Group III base fluids
Micropitting Prevention
Lubrication Effects - Additives

Field testing has shown widely varying results for the influence of sulfur-phosphorus (S-P) extreme pressure additives on micropitting. Some S-P additives appear to promote while others protect against Micropitting.
White Structure - a Form of Hydrogen Embrittlement from Oil Decomposition

Hydrogen generation → White structure formation → Cracking and flaking
White Structure Bearing Raceway Failure in Wind Turbine Gearbox

More hydrogen was detected in the bearing steel with White Structure flaking.

Hydrogen was generated by decomposition of the lubricant – phosphorus compounds were also found to have migrated into the White Structure.

Photos Courtesy of NSK Ltd.
Micropitting Prevention
Possible Additive Solutions

- **Additive activation temperature** appears to be a factor in determining micropitting performance.
- **Thermal stability and durability of the S-P additives** – resistance to chemical decomposition of the additive as temperature increases also affects the micropitting performance of the additives.
Gear Oil Formulators Strategy

Gear oil formulators must achieve an overall best balance of competing properties:

- Proper Viscosity
- Antiwear/extreme pressure/anti-scuff
- Micropitting/macropitting resistance
- Oxidation resistance
- Filterability
- Demulsibility
- Rust/corrosion resistance
- Foam control
- Deposit control
- Seal/Paint/Other material compatibility
Gear Oil Additive Systems Must be Thermally Stable

- Comparison of 5 Commercial Wind Turbine Gear Oil
- Deposits After Long Term @ 300ºF Thermal Stress Test in the Bottom of Erlenmeyer Flask
Thermal Decomposition of Gear Oil

- Increased filter plugging
- Increased viscosity
- Loss of boundary lubrication
- Promotion of hydrogen embrittlement
Foaming Tendency of **Used** Commercial Wind Turbine Gear Oils

0 ml of foam  130 ml of foam  710 ml of foam  900 ml of foam  0 ml of foam

190 ml of Fluid After 5 Minute Blowing Period (Real Time Photos) (ASTM D892 Test Protocol)
Gear Oil Foaming

- Loss of oil film in contact zone
- Oil pump cavitation
- Higher operating temperatures
- Gear box leaking
Demulsibility Performance of Commercial Wind Turbine Gear Oils

ASTM D1401 Demulsibility: Mix 40 ml water with 40 ml gear oil sample, allow to settle for 15 minutes
Oil and Water Mixtures

- Loss of oil film in contact zone
- Promotion of hydrogen embrittlement
- Additive depletion or inactivation
- Rust
- Filter plugging
- Greater suspension of wear particles in emulsion
SUMMARY: Preventing Micropitting Is the First Step to Extend Gear Box Life

• Micropitting affects both gear and bearing surfaces
• Both foaming and water emulsions disrupt the oil film between rolling and sliding surfaces
• Thermal stability and thermal durability of the basestock-additive combination is critical
• Keeping gear surfaces free of deposits allows the additive chemistry to work as designed and also reduces heat generation and retention