Oil Cleanliness in Wind Turbine Gearboxes

Robert Errichello and Jane Muller, Geartech

The Importance of Clean Oil

Researchers from London's Imperial College, Sayles and Macpherson1, showed rolling element bearing life can be increased up to seven times by changing from a 40-mm filter to a 3-mm filter. Their results also show that a gearbox must be clean after assembly or a fine filter will not be effective. This occurs because gears and bearings can suffer permanent damage in as little as 30 minutes during run-in, before a filter can remove built-in contamination.

The authors have found wide variation in gearbox performance from many inspections and failure analyses. Some gearboxes suffer severe contamination and fail. Other gearboxes operate with contaminant-free oil and run successfully for years. The authors believe varying performance is largely due to differences in the design of the gearbox and lubrication system, and differences in assembly cleanliness. Diligence is required throughout the manufacturing, assembly and initial run-in process to assure reliable gearboxes.

Many variables determine a gearbox's resistance to contamination and its performance.

Types of Contaminants

Wind turbines in desert environments are exposed to airborne dust during the hot season and moisture during the rainy season. Offshore turbines are constantly exposed to moisture.

Solid particle contaminants vary in hardness, friability and ductility, depending on the composition of the particle. Common contaminants like rust and black iron oxides have a Mohs hardness rating of five to six (on a scale of 1 to 10, with 10 being the hardest). Environmental dust, mostly silica, has a hardness rating of two to eight. Quarry dust has a rating of five to nine. From the manufacturing process, tool steel has a hardness rating of six to seven. Silicon carbide and aluminum oxide have a hardness rating of nine. Diamond tops the scale with a hardness rating of ten. The size, hardness and friability or ductility of the particle influence the amount of damage that the particle can cause.

Sources of Contamination

Contamination can enter gearboxes during manufacturing, be internally generated, ingested through breathers and seals, and inadvertently added during maintenance. All of these sources must be addressed to limit the impact that contamination can have on components.

Minimizing Built-in Contamination

Filters do not immediately remove built-in manufacturing debris. Consequently, permanent debris dents and other damage may occur during run-in, unless gearboxes are assembled in a clean room using clean assembly procedures and then filled with clean lubricant. There are many sources of contamination to eliminate long before the gearbox is placed into service.

For instance, the interior of gear housings should be painted with white epoxy sealer to provide a hard smooth surface that is easy to clean, seals porosity and seals in debris like casting sand. All components for assembly should be properly stored in a dry area prior to assembly. All gears and bearings should be covered, and bearings should be stored on their sides.

All components should be cleaned prior to assembly. Initial cleaning should be done in an area separate from the clean room, followed by final cleaning in the clean room just prior to assembly. All components should be carefully inspected to ensure they are clean and rust-free before assembly. Pay special attention to bolt holes, oil passages and other cavities that may contain dirt.

Gearboxes should be assembled in a clean room separate from any manufacturing processes such as machining, grinding, welding or deburring. Windows and doors should be adequately sealed to prevent contamination ingression and the ventilation system should be filtered so it provides clean, draft-free air. The floor should be painted and sealed so it is easily cleaned and the overhead structure should be painted and dust-free. No tow motors should be allowed in the clean room because they invariably introduce contaminants.

All work should be done by skilled technicians properly trained in gearbox assembly. All tools should be clean, appropriate for gearbox assembly, in good condition and properly calibrated.

Table 1. Required Oil Cleanliness for Wind Turbine Gearboxes

Source of Oil Sample	Required Cleanliness per ISO 4406:99
From new oil before adding to gearbox	16/14/11
From gearbox after factory testing	17/15/12
From gearbox during service	18/16/13

Table 1 gives guidelines for oil cleanliness designed to ensure adequate cleanliness of new oil used for factory tests, cleanliness of gearbox assembly and cleanliness of oil used in service.

Oil used for factory tests and service oil should be analyzed for cleanliness before adding to gearboxes. If test oil or service oil does not meet cleanliness requirements, it should be prefiltered using a filter with efficiency of b3>200.

A 3-um filter is suggested during factory testing to remove any contamination left after assembly or added during testing. After the factory test, the gearbox should be drained and flushed, and a new filter should be installed (if there is an online system). If oil does not meet cleanliness requirements after the factory test has been performed, then the gearbox assembly cleanliness should be improved.

If oil samples do not meet cleanliness requirements during service, there may be one or more failure modes in progress, or seals, breathers or maintenance procedures need to be improved.


Minimizing Internally Generated Contamination

Contaminants may also be generated internally. These particles are usually wear debris from gears, bearings, splines or other components resulting from micropitting, macropitting, adhesion, abrasion or fretting corrosion wear modes.

Micropitting is widespread in wind turbine gearboxes and is detrimental because it reduces gear accuracy, may cause gears to be noisy, and may escalate into other failure modes such as macropitting, scuffing or bending fatigue. Micropitting contaminates the lubricant with large amounts of iron particles.

The use of accurate and smooth surfaces, surface-hardened gears and splines, and high-viscosity lubricants can minimize internally generated wear debris. External and internal spline teeth should be nitrided and force-lubricated to prevent fretting corrosion. Annulus gears should be carburized or nitrided rather than through-hardened because through-hardened gears are relatively soft and prone to generating wear debris.

Material selection and heat treatment choices that determine material hardness are especially important design considerations. Filters cannot remove particles once they become embedded in softer gearbox components. Hard particles embedded in through-hardened annulus gears can cause polishing (fine-scale abrasive wear) on mating planet gears. This degrades gear accuracy and adds wear debris. Nonmetallic bearing cages should not be used because they are susceptible to particle embedment that can result in severe abrasive wear on rollers.

Wind turbines should not be parked for extended periods. Otherwise, fretting corrosion may occur on gear teeth, splines and bearings.

In addition, wet clutches and brakes should have separate lubrication systems to avoid contaminating the gearbox with their wear debris.

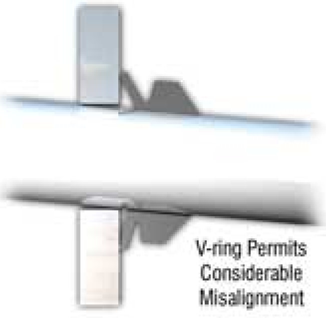
Minimizing Ingressed Contamination

Breathers are used to vent internal pressure when air enters through seals or when air within the gearbox expands and contracts during normal heating and cooling. The breather should have a filter and desiccant to prevent ingress of dust and water. It should be located in a clean, nonpressurized area away from contaminants such as brake dust and water. In especially harsh environments, the gearbox should be completely sealed and have an expansion chamber with a flexible diaphragm to accommodate pressure variation.

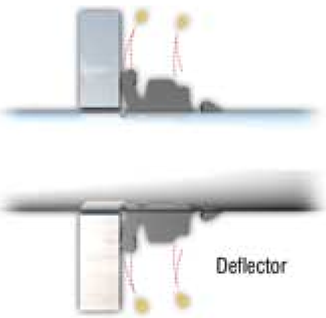
Most wind turbine gearboxes have labyrinth seals that provide long life and adequately seal in oil, but may allow contaminant ingression. Therefore, V-rings should be used as external seals. They are effective, but should have metal shields to protect them from damage.

Minimizing Contamination Added During Maintenance

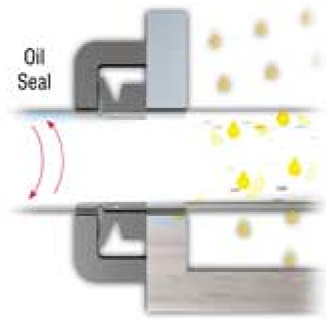
Maintenance in wind turbines is difficult and risky. Therefore, the gearbox, lubrication system, work platforms and nacelle housing should be designed to ensure maintenance tasks are readily accomplished in a safe manner. Breathers, filters, drain ports, fill ports, sample ports, dip sticks, magnetic plugs and inspection ports should be designed and located for easy maintenance and minimization of contamination.



All maintenance that involves opening the gearbox or lubrication system should be performed with good housekeeping procedures. Oil should be added from a filter cart connected to the gearbox with quick-connect couplings to minimize contaminants in the new oil and to minimize contaminant ingression during the transfer.



Many experiments have shown water in oil promotes micropitting. The mechanism is unproven, but may be related to hydrogen embrittlement. All lubricants are susceptible to water contamination, but ester-based lubricants and mineral oils with antiscuff additives are especially prone to absorbing water, and generally give lower fatigue life with high water content. To remove water, the lubricant should be changed or processed, or an offline filter with water absorption capability should be added.



Lubrication systems should be properly designed and carefully maintained to ensure gears receive an adequate amount of cool, clean and dry lubricant. Modern filters are compact and provide fine filtration and long life without creating large pressure drops. Offline filters provide fine filtration during operation and during turbine shutdown. Once the oil is clean, it should stay clean provided the gearbox and lubrication system were properly designed and seals, breathers and maintenance are adequate.

AGMA/AWEA 60062 discusses many elements of the lubrication system that determine oil cleanliness including the following:

- Lubricant type
- Lubricant viscosity
- Lubricant volume
- Online filter
- Offline filter
- Bypass valves
- Oil cooler
- Breather
- Oil sample ports
- Sampling procedures
- Control logic
- Condition monitoring

AGMA/AWEA 6006-AXX is an industrial standard written by the American Gear Manufacturers Association in cooperation with the American Wind Energy Association. It provides guidelines for specifying, selecting, designing, manufacturing, procuring, operating and maintaining gearboxes for use in wind turbines.

A lubricant-monitoring program can help prevent gear and bearing failures by showing when maintenance is required. Lubricant monitoring should include spectrographic and ferrographic analysis of contamination, particle counts and analysis of acidity, viscosity and water content. Used filter elements should be examined for wear debris and contaminants.

Mechanism and Significance of Debris Denting

Lubricant-borne solid particles much larger than elastohydrodynamic (EHL) film thickness can be entrained between gear teeth and between bearing rollers and raceways due to rolling action. Debris is subjected to enormous pressure under contact. Brittle particles fracture into smaller pieces, with some particles embedding in gear teeth and bearing surfaces, and other smaller fragments passing through the contacts. Ductile particles larger than the film thickness are able to pass through the contacts by the combined effects of flattening of particles and denting of surfaces.

Debris dents cause loss of EHL film thickness and lead to stress concentrations at shoulders around dents. Cyclic contacts at these sites generate pressure spikes, plastic deformation and tensile residual stresses that eventually initiate micropits, which may grow into macropits. Hard friable particles like titanium carbide pulverize into small fragments and promote abrasion, whereas hard ductile particles like tool steel create deep dents with high shoulders that promote fatigue.

References

1. Sayles, R. and Macpherson, P. (1982). Influence of Wear Debris on Rolling Contact Fatigue. Rolling Contact Fatigue of Bearing Steels. ASTM STP 771. p. 255-274.
2. AGMA/AWEA 6006-AXX. Standard for Design and Specification of Gearboxes for Wind Turbine Generator Systems.

Ensuring Clean Oil

- Paint gear housing interior with white epoxy sealer.
- Minimize built-in contamination by assembling gearboxes in a clean room and using clean assembly procedures.
- Ensure oil used for factory tests meets cleanliness requirements. If not, prefilter the test oil.
- Use a 3-mm filter during factory test to remove any contamination left after assembly or added during test. After factory test, drain the lubricant, flush the gearbox and install a new filter element.
- Monitor assembly cleanliness by analyzing oil after factory tests and improve assembly cleanliness if necessary.
- Minimize internally generated wear debris by using surface-hardened gear teeth and splines, smooth tooth surfaces and high-viscosity lubricants.
- Avoid nonmetallic bearing cages. t Do not park turbines for extended periods.
- Use separate lubrication systems for wet clutches and brakes.
- **Minimize ingressed contamination by using labyrinth seals, V-rings and a filtered, desiccant breather located in a clean, nonpressurized area.**
- For harsh environments, seal the gearbox and add an expansion chamber.
- Minimize contamination added during maintenance by designing for easy maintenance and following good housekeeping procedures. During oil fill, add prefiltered oil from a filter cart connected to the gearbox with quick-connect couplings.
- For circulating-oil systems, use fine filtration. Change or process lubricant to remove water, or use an offline filter with water absorption capability.
- For oil-bath systems, change lubricant at least annually or add an offline filter.
- Monitor service lubricant with spectrographic and ferrographic analysis, particle counts and analysis of acidity, viscosity and water content. Examine used filter elements for debris and contaminants.

Preventing Micropitting

The following guidelines summarize methods for preventing micropitting. Not every measure may be achievable, but as many as possible should be implemented.

Maximize Specific Film Thickness

Increase Oil Film Thickness

- Use highest practical oil viscosity

- Keep oil cool
- Use synthetic oil if gearbox sump temperature > 80°C (176°F)

Reduce Surface Roughness

- Avoid shot-peened tooth flanks, or polish flanks after shot peening
- Make hardest gear teeth as smooth as possible
- Run-in with special lubricant
- Prefilter lubricant and use a fine filter (3 mm) during run-in
- Keep oil cool during run-in
- Run-in gears using a series of increasing loads and appropriate speed
- Drain lubricant after run-in, flush the gearbox and change the filter

Optimize Gear Geometry

- Use at least 20 teeth in the pinion
- Use nonhunting gear ratio
- Use helical gears with axial contact ratio ³ 2.0 t Use aspect ratio £ 1.0 for spur and single-helical gears
- Use aspect ratio £ 2.0 for double-helical gears
- Minimize contact stress by specifying high accuracy and optimizing center distance, face width, pressure angle and helix angle
- Minimize specific sliding by using profile shift
- Use proper profile and lead modification

Optimize Metallurgy

- Maximize pinion hardness
- Make pinions 2 HRC points harder than gears
- Use = 20 percent retained austenite

Optimize Lubricant Properties

- Use oil with high micropitting resistance as determined by testing
- Use oil with low traction coefficient
- Use oil with high pressure-viscosity coefficient
- Avoid oils with aggressive antiscuff additives
- Avoid oils with viscosity index improvers
- Keep oil cool
- Keep oil free of solid contaminants
- **Keep oil dry**

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