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REAPING THE RENEWABLE WHIRLWIND

THE ROLE OF OIL ANALYSIS IN WIND TURBINE GEARBOX RELIABILITY

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In his address to parliament in Cape Town on the 3rd of February 1960, British Prime Minister Harold Macmillan said that the winds of change were blowing through Africa. He was referring to the decolonisation and subsequent self-determination of African states.

Fast forward 54 years to 2014, and on the eve of our fifth South African democratic elections it seems poetic that once again the winds of change are blowing through South Africa but this time it is not a political revolution that is set to change the landscape of our beautiful country, but a green revolution in renewable energy.

South Africa's Integrated Resource Plan (IRP), under the leadership of the Department of Energy (DoE), envisages renewable energy contributing to 42% or 17.8GW of the country's new generation capacity by 2030. One of the ways they plan to achieve this is with 8.4GW of wind generated power.

The DoE's Renewable Energy IPP (Independent Power Producer) Procurement Programme has already overseen the completion of three successful bidding windows with a fourth bidding window to start in July 2014. The approved bids from rounds one, two and three combined with the proposed bids for round four will result in the construction of numerous wind farms over the next 10 years that will collectively house in the region of 2500 wind turbines.

The estimated life span of wind turbines is about 20 years, compared to conventional steam turbine generator units that have averaged 40 years. The failure rate of wind turbines is about three times higher than that of conventional generators and this has historically been attributed to constantly changing loads experienced by the wind turbine as a result of environmental variants.

Due to these highly variable operational conditions the mechanical stress placed on wind turbines is incomparable in any other form of power generation and they consequently require a high degree of maintenance to provide cost effective and reliable power output throughout their expected 20 year life cycle. The wind turbine gearbox is the most critical component in terms of high failure rates and down time.

These premature gearbox failures are a leading maintenance expense that can substantially lower the profit margin of a wind turbine

Nacelle housing gearbox and generator being hoisted during installations (courtesy of Nordex)

operation, as they typically result in component replacement. Despite significant advancements in gearbox design, they remain an operation and maintenance cost driver due to the very high associated repair costs coupled with a high likelihood of failure through much of the wind turbine's life cycle.

Ensuring long-term asset reliability and achieving low operation and maintenance costs are key drivers to the economic and technical viability of wind turbines becoming a primary renewable energy source in South Africa.

Oil analysis, along with other condition monitoring tools, offers the potential to effectively manage gearbox maintenance by detecting early damage as well as tracking the severity of the damage. It is for this reason that most OEM's recommend routine oil analysis as part of an effective maintenance strategy.

Routine oil analysis is one of the most widely used predictive / proactive maintenance strategies for wind turbines and utilises a test slate that evaluates the condition of the in-service lubricant and helps evaluate the condition of internal mechanical components.

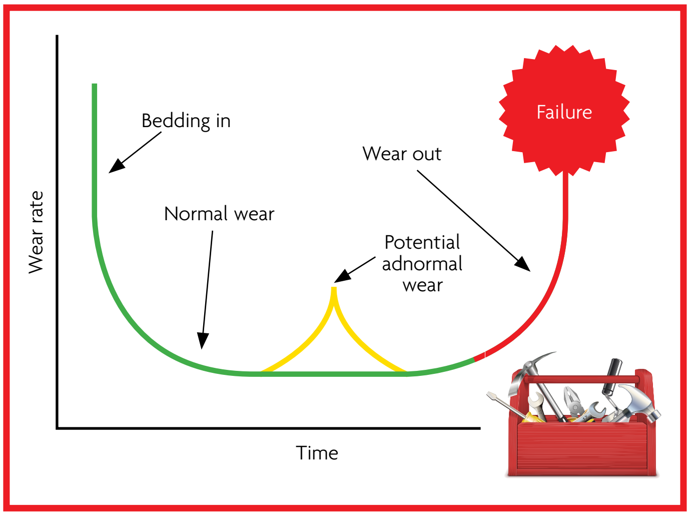
In this Technical Bulletin, we will look at what oil analysis can measure in terms of the first three functions of oil analysis,

Routine maintenance performed up-tower (courtesy of Siemens)

which are; to detect abnormal wear, oil degradation and contamination. Active monitoring of the above provides early warning of abnormal operating conditions that can lead to catastrophic failures in a wind turbine if not corrected.

DETECTING ABNORMAL WEAR

The fundamental concept behind monitoring wear appears uncomplicated: trend the metal wear rates for sudden increases that indicate a change in the system's health.



Bathtub curve

Wear metal generation rates are often described as following a bathtub curve. The curve represents wear generated over the lifetime of a typical wearing component, with elevated wear levels during bedding-in, followed by prolonged periods of relatively constant wear levels, followed by the onset of severe wear and an exponential increase in metal generation leading to eventual failure at the end of the component's life.

While this is a sound theory, wear debris generation is a complex phenomenon. Wear rates can increase and decrease throughout the life time of the gearbox due to several factors such as operating loads, lubricant quality, fault progression etc. Even during fault progression, wear rates are highly mutable depending on the microstructural material properties of the wind turbine gearbox components e.g. cylindrical roller bearings.

Commercial oil laboratories employ varying techniques when it comes to detecting (quantifying and classifying) wear particles in oil, each with its own strengths and limitations. The most widely used and OEM-requested laboratory techniques will be described below.

SPECTROMETRIC ANALYSIS

The spectrometer is used to determine the presence and concentration of different elements in the oil. These are measured in PPM (parts per million). The measured elements are usually divided into three broad categories: wear metals such as iron, contaminants such as silicon and oil additives such as phosphorus.

Wind turbine gear oil analysis usually requires close monitoring of iron and copper wear rates as these metals are most commonly used in the construction of internal gearbox components. In terms of wear metals detected in the oil, the iron wear rate is usually the highest reading, because almost everything in a gearbox is made from different steel alloys. Sources of iron include bearings, shafts, and gears, while copper wear usually originates from bronze alloy bearing cages.

Unfortunately the spectrometer can only measure very small particles, usually less than eight microns in size. The instrument cannot "see" larger particles that might indicate a severe wear situation is developing.

FERROUS DEBRIS MONITOR

The ferrous debris monitor provides a measure of the total ferrous content of the oil sample and from this measurement the total amount of ferrous (iron) debris can be determined irrespective of the particle's size.

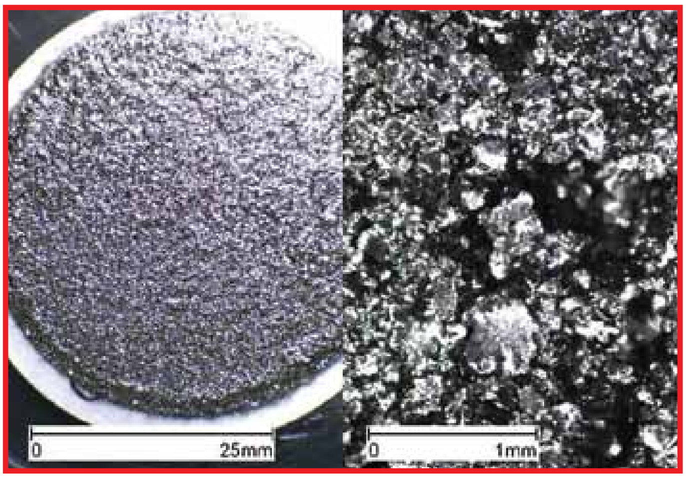
Wear metal particles detected by spectroscopy are typically less than eight microns in size. These small particles can be generated by rubbing wear or fretting corrosion. Larger particles are generated by more severe wear modes such as fatigue wear, pitting and spalling. These larger ferrous particles present in the used oil sample can be detected by using this method. The PQ index is not an actual concentration measurement, but it can be compared to the iron (ppm) reading obtained from the spectrometric analysis.

If the PQ index is smaller than the iron (ppm) reading, then it is unlikely that particles larger than eight microns are present. Alternately, if the PQ index increases significantly while the iron reading remains consistent, then larger ferrous particles are being generated and further analysis into the cause of the elevated PQ should be performed.

MPE (MICROSCOPIC PARTICLE EXAMINATION)

In terms of wear particles, their morphology and quantity provide direct insight into overall gearbox health.

An MPE is performed by filtering the oil through a membrane patch of a known micron rating and any debris present is examined under a microscope. The membrane patch is examined for wear, contamination and colour.



An MPE from a wind turbine gearbox

An MPE can provide clues to the source of the debris and the potential seriousness of a problem that may be causing it. The individual particles themselves are not categorised, but instead observations are recorded for trending purposes using a size and concentration reference matrix.

ANALYTICAL FERROGRAPHY

Analytical ferrography involves observing and categorising particle size, shape, colour and surface texture under magnification.

Evaluating the concentration, size, shape, composition, and condition of the particles indicates where and how they were generated. The particle's composition indicates its source and the particle's shape reveals how it was generated. Abrasion, adhesion, fatigue, sliding, and rolling contact wear modes each generate a characteristic particle type in terms of its shape and surface condition.

Particle composition is broken into categories that include: ferrous wear, white metal, copper, and fibres. Ferrous particles can further be identified as steel, cast iron, dark oxides, or red oxides (rust). A skilled analyst can also determine if metallic wear particles are caused by cutting wear versus rolling or sliding wear. Wear debris monitoring has been demonstrated to be an effective means of detecting gear and bearing fault initiation.

The main particle types related to the fatigue process encountered in wind turbine gearboxes are: laminar micro-particles (micropitting), laminar particles, chunky fatigue particles and spheres.

Analytical ferrography can be a powerful diagnostic tool in oil analysis. When implemented correctly it provides a tremendous amount of information about the machine under operation.

COOL, CLEAN AND DRY

It is often said that there are three key requirements for maintaining the condition of wind turbine gear oil: keep it cool, keep it clean and keep it dry. In truth this applies to any mechanical system but these requirements, in the context of this paper, relate to the monitoring of oil degradation and contamination of wind turbines.

DETECT OIL DEGRADATION

The different modes and severities of oil degradation are dependent upon the oil type, application and exposure to contaminants. Oil degrades over time due to its ability to react with oxygen in the atmosphere. This process is known as oxidation. Oxidation causes the viscosity to increase and acids to form in the oil. The rate at which this occurs can be increased by high operating temperature and the presence of contaminants.

In wind turbine gearboxes, oxidation also results in metal corrosion, varnish formation, foaming/air entrainment, poor water demulsibility and filter plugging.

The tests below are usually performed on wind turbine gearbox oils to detect oil degradation/oxidation.

KINEMATIC VISCOSITY (KV)

Kinematic viscosity is defined as a fluid's resistance to flow under gravity, at a specified temperature and this in turn determines the thickness of the oil film that prevents contact between metal surfaces. KV is measured in centistokes (cSt) and one centistoke is one millimetre squared per second. Typically, KV is reported at 40°C (KV40) and 100°C (KV100) for wind turbine gearbox oil analysis.

A lubricant has many functions to perform and these can be categorised into four fundamental groups: reduction of wear, removal of contaminants, removal of heat and acting as a structural material. All these functions are negatively impacted if the viscosity of the oil falls outside of the intended viscosity range i.e. too high or too low. If the viscosity is not correct for the load, the oil film cannot be adequately established at the friction point. Heat and contamination are not carried away at the proper rate, and the oil cannot sufficiently protect the component. A lubricant with the improper viscosity will lead to overheating, accelerated wear, and ultimately failure of the component. It is for this reason that viscosity is considered the most important physical property of a lubricant.

Trending of viscosity data is important as deviations from the norm may indicate base oil degradation, additive depletion or the use of an incorrect lubricant.

When the oil's viscosity increases, it is usually due to oxidation or degradation typically as a result of extended oil drain intervals, high operating temperatures, the presence of water, the presence of other oxidation catalysts or the addition of an incorrect lubricant.

Decreases in oil viscosity are attributed to degradation of the viscosity index improver (VII) additive in the oil as a result of shear or due to the use of an incorrect lubricant during refilling and topping-up procedures.

A low viscosity (<15% of new KV) is generally considered to be more problematic as this results in a reduced film thickness and the consequent propagation of fatigue cracks associated with micropitting. Micropitting is a surface fatigue phenomenon resulting in superficial damage that appears in high rolling contacts and is characterised by the presence of small pits on the tooth surface. They first appear in the rolling zone of the gears and then progress towards the root (dedendum) of the gear.

Micropitting causes tooth profile wear (deviations in the shape of the tooth), which increases vibration and noise, concentrates loads on smaller tooth areas increasing stress on gear teeth and shortening gear life.

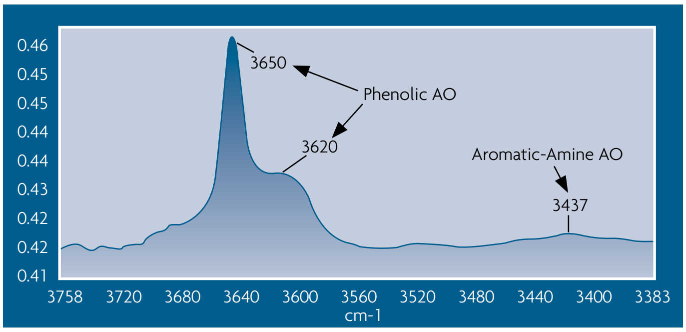
VISCOSITY INDEX (VI)

The viscosity index characterises the effect of temperature on an oil's viscosity and is of particular importance in applications where operating temperatures vary significantly. The VI can change when the lubricant degrades (chemically "breaks down") or degradation by-products accumulate. The kinematic viscosity at 40°C and 100ºC are used to calculate the viscosity index.

FOURIER TRANSFORM INFRARED (FTIR)

Another technique employed to detect base oil oxidation is Fourier Transform Infrared (FTIR) analysis. FTIR analysis effectively measures the concentration of various organic or metallo-organic material present in the oil. When oil is oxidised, the hydrocarbon oil molecules can become restructured into soluble and insoluble oxidation by-products as a result of the sequential addition of oxygen to the base oil molecules. FTIR measures the accumulation of these by-products.

FTIR produces an infrared (IR) spectrum that is often referred to as the 'fingerprint' of the oil as it contains specific features of the chemical composition of the oil. The IR spectrum can be used to identify types of additives, trend oxidation and nitration by-products that could form as a result of high operating temperatures and thermal degradation caused by aeration/foaming. These are all important indicators of the lubricant's ability to perform its basic functions as detailed earlier on in this paper.



FTIR Spectrum Showing Antioxidants Courtesy of Noria Corporation

The usefulness of FTIR in determining oxidation is dependent on the base oil used to formulate the lubricant. Synthetic lubricants often contain ester compounds which have a significant peak in the infrared spectra area where the oxidation level for mineral oils is measured.

Despite this, several studies performed by international oil analysis laboratories have shown a correlation between the FTIR oxidation reading of synthetic oils and other degradation parameters measured in the oil. In synthetic oils the oxidation value by FTIR in itself is not necessarily useful but trending it in conjunction with other parameters can be quite revealing.

TOTAL ACID NUMBER (TAN)

The total acid number is a quantitative measure of acidic compounds in the oil that are generated as a result of oxidation and the formation of acidic degradation by-products.

The TAN is also utilised as a means to determine optimal drain intervals. The reasoning behind this is as follows: an increased TAN could be the result of increased oxidation, and if oxidation is a consequence of oil ageing, then it follows that the TAN could be used as an indicator of oil serviceability, as high TAN levels could also indicate additive depletion (of anti-oxidant additives).

The TAN of the new oil will vary based on the base oil and additive package. As the TAN value of the oil increases, viscosity rises and the lubricating potential of the oil is compromised, leading to increased wear.

In addition, the corrosive tendencies of the oil will increase further exacerbating component wear. Condemning limits are dependent on the lubricant in use and the environmental conditions in which the wind turbine will operate, but as a general rule, an increase in the TAN of more than 1mg KOH/g above the starting TAN of the new oil is considered cause for concern.

REMAINING USEFUL LIFE (RULER)

A change in viscosity and TAN is usually a lagging indicator of oxidation. Despite the validity of all of these measurements, the fact remains that they all reveal damage to the base oil after it has occurred. A preferable scenario would be to evaluate the oil's ability to resist further oxidation by measuring the anti-oxidant additive reserves, in essence, its remaining useful life.

Oil oxidation is a series of chemical reactions both initiated and propagated by reactive chemicals (free-radicals) within the oil. As the oil degrades, a sequence of events occurs, each of which can be measured with oil analysis. At first, the anti-oxidant additive package depletes and then the base oil oxidises. The anti-oxidant additive is sacrificial - it is there to protect the base oil from oxidation. The most common anti-oxidant additives found in wind turbine gear oils are phenolic inhibitors, (these work to neutralise the free-radicals that cause oxidation) and aromatic amines (these work to trap free-radicals).

The RULER test is a proactive technique used for measuring anti-oxidant depletion rates and calculating the remaining useful life of the oil.

Working in the proactive domain, maintenance staff can perform a partial drain and fill or top-treat the oil to replenish the anti-oxidant concentration to avoid base oil degradation.

Likewise, for planning and scheduling purposes, RULER monitoring provides management with a significant forewarning of impending oil failure (assuming no intervention to affect the chemistry), which allows the event to be handled in such a way that cost and impact on the organisation are minimised.

It is for this reason that RULER analysis is ideally suited to monitoring wind turbine gearbox oil degradation caused by exposure to elevated temperatures and oxidation. RULER along with TAN is often utilised to establish optimal oil drain intervals.

The rate of anti-oxidant depletion versus time (anti-oxidant depletion trend) can be monitored and used to predict the right oil change intervals. The established RULER limit value for most wind turbine gear oils is 25% of the new oil value.

DETECT CONTAMINATION

The third major function of oil analysis is to monitor levels of contamination. Contaminants can be classified as either internal or external. Internal contaminants are generated within the mechanical system such as wear debris from gears and bearings. External contaminants are substances that exist in the environment but should not be in the oil. The most common ones are dirt, air and water. Contaminants can be directly damaging to the machinery being lubricated, dirt is abrasive and can cause components to wear abnormally; and water causes metals to rust. Contaminants can also cause the oil to degrade which, in turn, may have an adverse effect on a mechanical system.

Over the years, wind turbine manufacturers have increasingly focused on oil quality and cleanliness, which has a huge impact on the lifetime of bearings and the performance of the gearbox. This is because higher output means more strain on gears, increased mechanical wear and a greater chance of oil contamination. The three main sources of oil contamination in wind turbine gearboxes are moisture, solid particles and air (foam and entrained air). Contamination can enter gearboxes during manufacturing, be internally generated, ingested through breathers and seals, and accidentally added during maintenance. A recent edition of the publication Wind Power Monthly quoted a major wind turbine gearbox manufacturer as saying that over 70% of the damage done to the gearbox was a direct result of particles and moisture contamination.

When it comes to contamination control in wind turbine gearboxes, the adage "if you can't measure it, you can't manage it" is most apt. With that in mind, what follows is a brief description of the three most commonly encountered yet detrimental contaminants in wind turbine gearboxes.

AIR CONTAMINATION

Air can exist in oil in four different states: dissolved, entrained, foam and free.

Dissolved air exists as individual molecules which are similar to carbon dioxide dissolved in carbonated soft drinks. This type of air is invisible and difficult to detect. Entrained air in oil is comprised of tiny air bubbles suspended in the oil. This type of air contamination is considered to be the most destructive and can usually be identified by the oil having a cloudy appearance. Foam is a collection of relatively large air bubbles that accumulate on or near the surface of the oil. In the free phase, there are air pockets trapped in dead zones within the mechanical system.

Foam and entrained air are the two problematic states of air contamination most experienced in wind turbine gearboxes.

Foaming and entrained air can damage lubricating oil by increasing the rate of oxidation and thermal degradation, depleting additives, reducing its heat transfer capabilities and reducing its film strength. Oil molecules oxidise when they come into contact with oxygen. That being the case, it stands to reason that an increase in entrained air results in increased exposure to oxygen which consequently causes an increase in oil oxidation.

To make matters worse, foam is also an efficient thermal insulator, so the temperature of the oil can become difficult to control. When oil runs hot, viscosity runs thin which degrades film strength in frictional zones, leading to wear.

The most common causes of foaming are:

- Water contamination
- Solids contamination
- Depleted anti-foamant additive
- Mechanical issues (causing excessive aeration of the fluid i.e. low oil level)
- Overfilling of the sump in splash and bath lubricated compartments
- Cross contamination of the fluid with the wrong lubricant
- Contamination of the fluid with grease
- Over treating with anti-foamant additive

Foaming is a serious concern in wind turbine gearboxes and is generally the result of a mechanical problem or a chemical issue relating to the condition of the oil. Performing a foaming tendency and air release test can help differentiate between the two causes of foaming as described in the below chart.

	Analysis	
	Air Release (ASTM D3427)	Foam Stability (ASTM D892)
Mechanical problem (excessive aeration)	Same as new oil	Same as new oil
Air Detrainment problem (oil does not release air bubbles)	Increase from new oil	Same as new oil
Depleted anti-foamant additive	Increase from new oil	Increase from new oil

Courtesy of Noria Corporation

Foaming tendency is a multi-stage test used to determine the oil's tendency to entrap air and cause oil foaming as well as the ability of the oil to dissipate the foam (foam stability). The foaming tendency is the amount of foam formed on the completion of the test and the foam stability is how long it takes for the foam to collapse.

With air release, the time taken for the oil to release a specified amount of air under predetermined conditions is measured. Wind turbine gearbox oil limits for both foaming tendency and air release are dependent on the oil used.

WATER CONTAMINATION

Water can exist in three phases in oil: dissolved, emulsified and free.

Different oils have different water contamination handling abilities depending on the base stock and additives used during formulation. The amount of water an oil can carry in solution is known as the saturation point. Once this point is reached, any additional water added will form an emulsion or fall out of suspension as free water.

Below saturation level, the molecules of water are dispersed alongside the oil molecules resulting in water in the oil that is not visible. This is known as dissolved water, the least dangerous water state to a lubricated system. When the amount of dissolved water exceeds the saturation point, the oil is no longer able to absorb more water, resulting in emulsified water. This is characterised by a hazy or cloudy appearance of the oil. Further increases in water content in the oil will result in separate levels of oil and water forming. This state is known as free water.

Wind turbine operators have observed that water entrainment in gearboxes can significantly degrade the gearbox lubricant by causing the lubricant to foam or lose its ability to create a sufficient film thickness for elastohydrodynamic (EHL) contact. Water contamination can also cause the formation of rust on internal components, or react with the additives in the lubricant and diminish their effectiveness. There is also the issue of accelerated wear of gearbox components by hydrogen embrittlement. Hydrogen embrittlement is the process by which various metals, including high-strength steel, become brittle and fracture following exposure to hydrogen which is part of the water molecule.

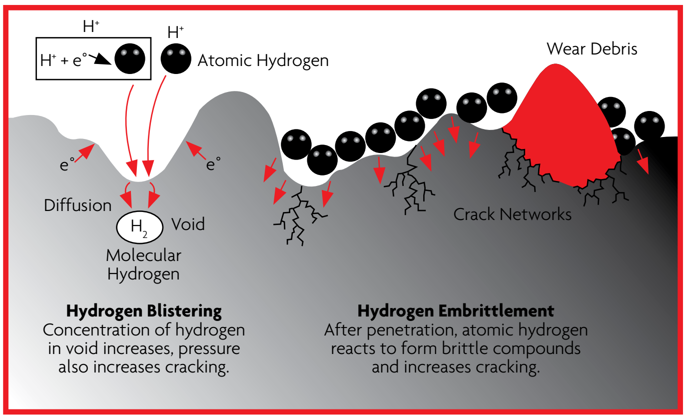
Water contamination problems in wind turbine gearboxes

Problem	Summary
Corrosion	Ionic currents in aqueous solution; pitting, leakage, breakage
Additive drop-out	Polar hydrophilic additives depletion, also breaking colloidal suspensions of additive particles; loss of additives, parts fouling
Microbial growth	Colonisation of oils by bacteria and/or fungi; acids, fouling slimes; health issue
Hydrolysis	Decomposition of ester-based fluids and additives; loss of oil properties, acid and sometimes gel formation
Accelerated oil oxidation	Especially if metal wear debris present, rate of oil oxidation increases by two orders of magnitude; oil thickening, acidity
Surface-initiated Fatigue Spelling	Water dissociates into O2 and H2 at tips of propagating cracks. H2 migrates into and weakens steel by hydrogen embrittlement; cracks spread faster, reducing life of rolling elements, resulting in surface pits and craters

Courtesy of Power engineering magazine

Several different techniques are used by oil analysis laboratories to determine the moisture content of lubricating oil but Karl Fisher titration is the preferred method by wind turbine gearbox manufacturers and lubricant suppliers, as even small amounts (<100 ppm) of water contamination can be detected in the oil using this method.

Through research performed by a reputable bearing manufacturer, it was found that just 1000 ppm of water contamination could reduce ball bearing life by 70%. So in terms of condemning limits, best practice suggests maintaining water levels at or below half of the saturation level of the oil at its operating temperature. Thus, if the saturation level is 1000 ppm at 50°C, the caution level should be set at 500 ppm, with the critical level at 1000 ppm.



Hydrogen embrittlement mechanism courtesy of Noria Corporation

OIL CLEANLINESS

Particle counting involves measuring the cleanliness of the oil and can also be used to evaluate the effectiveness of lubricant filters.

Very much like water, particulate contamination is very damaging to wind turbine gearboxes. It is for this reason that wind turbine manufacturers have increasingly focused on oil cleanliness. Oil cleanliness is critical to establishing equipment reliability, especially as there is a direct correlation between oil cleanliness and component life.

In this technique the number of particles per millilitre of oil is counted in a variety of size ranges starting at four micron and going up to 100 micron. The total number of particles greater than four, six and 14 micron are evaluated and assigned range numbers that indicate the cleanliness of the oil.

It is actually particles of approximately the same size as the machine clearances that have the greatest destructive potential. Particles the size of or slightly larger than the oil film thickness enter the contact zone and damage surfaces.

While this technique is effective in determining the number and size of particles being generated, particle counting will not identify what the particles are. They could be metallic – both ferrous and non-ferrous, silica, silt, filter fibres, bacteria colonies, varnish agglomerations, water, etc.

The American Wind Energy Association and the American Gear Manufacturers Association have released a technical standard that sets attainable oil cleanliness targets. The standard is entitled "ANSI/AGMA/AWEA 6006-A01: Design and Specification of Gearboxes for Wind Turbines".

Source of sample	ISO Code
Oil added to gearbox	16/14/11
Gearbox after factory test	17/15/12
Gearbox after 24-72 hour service	17/15/12
Gearbox in service	18/16/13

ANSI/AGMA/AWEA 6006-A01 Oil cleanliness recommendations

With rigorous particle contamination control, bearing life can increase substantially resulting in greater gearbox reliability, uptime and energy production, extended warranty periods and a higher return on investment.

Oil analysis provides a solid foundation on which to build an effective condition monitoring programme in many applications. In the case of wind turbine gearboxes, oil analysis has the potential to reduce unscheduled maintenance, improve reliability and extend service life. The oil analysis tests profiled in this paper can help wind farm operators get maximum value from their oil sampling programme. When these tests are performed on a routine basis and the results properly analysed, oil analysis can facilitate the maintenance of wind turbine gearboxes and, ultimately, support more widespread acceptance of this promising form of power generation in South Africa.

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