# Understanding the Root Causes of Axial Cracking in Wind Turbine Gearbox Bearings

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## Introduction

*Modern Wind turbines are an important piece of our energy mix. Unfortunately, gearbox life issues have impacted their financial payback. Axial cracks in bearing raceways have become the major cause of premature gearbox failures in the latest generation of wind turbines, shortening life to as little as 1-2 years once damage is initiated. Axial crack failures in gearbox bearings are rare in other industries. Why damage is so common in wind turbines is a mystery that is the subject of intense research. The root cause must be understood to successfully find the solution.*

*This paper is divided into two parts. Part 1 is a review of the latest research on the phenomenon of axial cracking. It discusses how these axial cracks grow from smaller cracks that have a white color when they are sectioned and etched. These White Etch Cracks (WEC) can originate from microscopic super-hard areas that also show up white when sectioned and etched. These areas in which cracks occur are called White Etch Area (WEA) damage. It appears that a threshold of rapid and severe plastic deformation must be exceeded to create these hard microscopic WEA areas. But what event in a wind turbine could cause such rapid and severe loading on the bearings? That is the subject of Part 2. It is based on recent research and field monitoring by the authors that was presented at the NREL GRC in February, 2013, along with additional research and field data generated since that presentation.*

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## Part 1:
## Axial Cracks < White Etch Cracks < White Etch Areas < Impact Loading & Rapid Plastic Deformation

### Axial Cracking

Axial cracks on inner rings of high speed and intermediate speed bearings have become a leading cause of wind turbine gearbox life problems. See Figs. 1 and 2. Numerous technical papers have been written on axial cracking in the past couple of years, many of which have focused on why this unusual bearing phenomenon is so prevalent in wind turbine gearboxes. Some of these publications are referenced with footnotes and listed at the end of this paper.

Fig. 1 A single axial crack that has propagated completely through the inner ring.

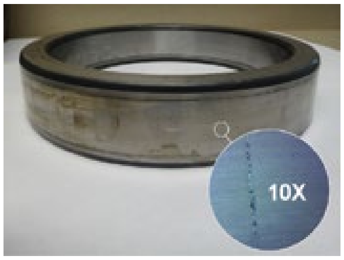

Fig. 2 Multiple axial cracks on the inner ring in early stages.

Wind turbine bearings are selected to meet a 20-year design life, with a low likelihood of failure. Most manufacturers follow Germanischer Lloyd (GL) guidelines for gearbox bearings. GL requires that gearbox bearings be analyzed for Rolling Contact Fatigue (RCF) resulting in the calculated life being at least 130,000 hours with a likelihood of failure at less than 10%.[6] If wind turbine gearboxes meet these design criteria, how can axial cracking failure rates be so high and often occur within the first or second year of operation? How can it be that a bearing that has been analyzed using well-understood and validated methodologies will likely fail much sooner than predicted? The answer lies in the fact that the axial cracking failure mode differs from the classic RCF failure mode. RCF failures are caused by damage to the bearing material that accumulates over time – at well understood rates. The axial cracking failures are relatively recent phenomena and their modes of failure are much less understood.

Why does axial cracking failure mode occur in the inner ring of a bearing? This is mainly due to the inner ring being typically mounted to a shaft with an interference fit. The ring is heated during assembly onto the shaft. When the ring cools, it shrinks – holding the ring in place, but also creating tensile stress in the ring that increases the possibilities for axial cracking.[6] An axial crack failure of the inner ring can be caused by excessive hoop stresses during installation but this does not appear to be the general case in the wind industry. Microscopic, white-colored areas at the edge of the cracks when the bearings are sectioned and etched are the key indicator that these are not merely standard hoop stress failures. These cracks are termed White Etch Cracks (WEC) and are commonly found in through-hardened bearing races.

## White Etch Area (WEA) - Subsurface Microscopic Material Alteration

Detailed failure analysis of axially cracked bearings reveals that the White Etch Areas also appear in subsurface cracks and even in areas where cracks have not yet started. WEA damage is actually a microstructural alteration of the inner ring material, creating tiny super-hard areas (30 - 50% harder than the surrounding area)[2, 3, 6] just below the raceway surface. These areas act like inclusions in the steel (Fig. 3 shows a microscopic WEA formation with nano hardness measurements).

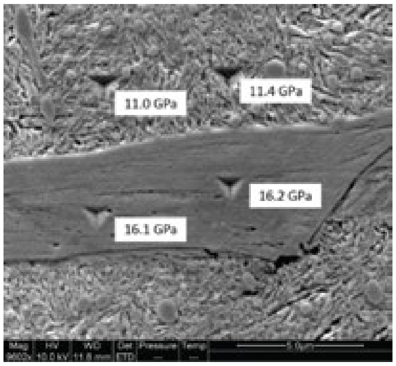

Fig. 3. A microscopic WEA formation with nano hardness measurements showing a 44% increase in hardness. Courtesy A. Greco et al[1]

Once an event occurs that initiates the subsurface WEA formations, normal rolling action of the bearing can cause cracks to start at the junction of these inclusion-like areas. The crack will inevitably propagate to the surface and become a White Etch Crack (WEC), which can grow axially across the raceway and prematurely fail the bearing.

Many research papers recognize two primary mechanisms for WEA damage: hydrogen-induced WEA and stress-induced WEA. Hydrogen WEA is believed to be driven by corrosion, water contamination, electrical currents and/or aggressive oil additives that can worsen cracks once they appear on the surface. But what events initiate these surface cracks? This paper focuses on understanding the events that can initiate subsurface stress-induced WEA damage and Part 2 will show that these same events could cause surface cracking, as well. This can explain how hydrogen-induced WEA is initiated in the first place.

Stress-induced WEA damage in the bearing inner ring must come from an event that can cause the roller to exert high subsurface stresses simultaneously with rapid strain rates. Possible WEA mechanisms mentioned in recent papers include:

- **Impact Loading –** sudden loads that can cause high stress and strain;
- **Surface Traction –** frictional contact between the rollers and races that produce high surface and subsurface stresses;
- **Severe Plastic Deformation (SPD) –** subsurface stress high enough to cause microscopic deformation;
- **Rapid Plastic Deformation (Adiabatic Shear Bands, ASB) –** subsurface plastic deformation so rapid that the heat generated cannot be dissipated and thus directly alters the material to create ferrite microstructures.

All four of these mechanisms are related and can occur at the same time. For instance, WEA damage can be created in the Lab with ballistic impacts, where all four of these WEA mechanisms have been shown to act simultaneously. When a bullet passes through metal, the impact causes **surface traction** and **severe and rapid plastic deformation,** creating **Adiabatic Shear Bands** (ASB).

When the WEA cracks become visible on the inner ring surface, they are termed White Etch Cracks (WEC). When WEA damage causes flaking or spalling, it may be termed White Structure Flaking (WSF). This can occur with carborized raceways. See Figs. 1, 2 and 4. Either way, the damage starts with the creation of White Etch Areas.

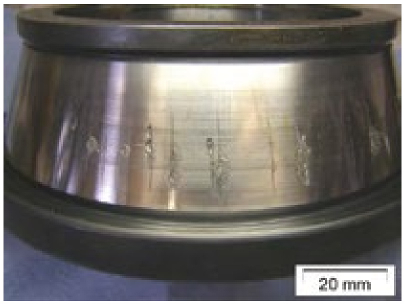

Fig. 4 shows White Etch Cracks (WECs) and White Surface Flaking (WSF) on the inner ring of a tapered roller bearing. Evidence suggests that both were initiated by WEA microstructural alterations in the steel subsurface.

Courtesy A. Greco et al[1]

## Impact Loads & Rapid and Severe Plastic Deformation (Adiabatic Shear Bands)

An adiabatic shear band (ASB) is an area within a base material that has been transformed by microscopic, localized heating during rapid and severe plastic deformation. Since the 1960s, adiabatic shear bands have been studied extensively because of their importance as a failure mode in areas such as high-speed metal forming and cutting, various types of ballistic impact, as well as vehicle crashes. "Adiabatic" is a thermodynamic term simply meaning an absence of heat transfer – the heat produced is retained in the zone where it is created. These shear bands are usually very narrow, typically .0002 to .020 inches. In steel, these bands are in fact WEA damage where fatigue cracks can initiate. There is a threshold of instantaneous high stress and strain rate where microscopic plastic deformation creates heat so fast that it cannot escape. The subsurface metal momentarily softens and transforms the material as it cools into an altered microstructure. Severe deformation that occurs slowly will let the heat escape and will not produce ASBs or WEA damage. Thus a stamped metal part may show a similar degree of plastic deformation as a bullet hole but because the strain rate is lower, ASBs and WEA damage can be avoided.

In bearing material, the heat from the rapid plastic deformation can cause a microstructural transformation of the hardened bearing steel into a sliver of super-hard ferrite that appears white when sectioned and etched, WEA damage. A band of WEA damage is not required to fail the bearing. A single sliver of this WEA damage can act as an inclusion to initiate White Etch Cracks that eventually propagate to the surface and across the bearing raceway surface.[6]

Bearing manufacturers have continuously improved the life of roller bearings by improving the purity and quality of the steel used in their products. By minimizing hard inclusions and stringers (elongated carbide or sulfide inclusions), they minimize the potential places where cracks can initiate and propagate. These efforts have achieved an impressive 10-fold increase in bearing life as predicted by the standard Rolling Contact Fatigue (RCF) method used by bearing manufacturers to calculate $L_{10}$ life.[2,6] Unfortunately, all the efforts to make super-clean steel can be wasted by events in a wind turbine's operation that initiates WEA damage, mimicking inclusions less than .04 inches (1 mm) below the raceway surface. This depth coincides with the depth of maximum shear stresses under the bearing raceway during normal Hertzian loading of the rollers. Also, this is the worst possible location for an inclusion-like impurity to be located, leading to shortened bearing surface fatigue life and axial cracks. Once started, WEA damage can reduce the bearing life to just 1% to 10% of predicted life as calculated with standard rolling contact fatigue formulas.[2] This explanation shows how WEA induced axial cracks can cause bearings to fail within one to two years of operation.

What events in a wind turbine could create impact loads and rapid plastic deformation significant enough to initiate the WEA damage? Some researchers have concluded that, "A wind turbine exposed to an extreme event, such as a power loss or emergency stop, could produce the localized deformation energy needed for ASB formation".[3]

## Part 2

## Emergency Stops > Transient Torque Reversals > Rapid Bearing Load Zone Reversal > Impact Loads and Rapid Plastic Deformation of Bearing Material

### Emergency Stops and Other Transient Turbine Events

All the recent papers on bearing axial cracking support impact loading and emergency stops as likely contributors to WEA damage. Wind professionals have long recognized that emergency stops and other sudden stops can put extreme loading into all turbine drive components. Many have even noted a relationship between E-stops and gearbox life. There is a growing awareness that it is the Transient Torque Reversals (TTRs) during these severe stopping events that may be the source of damaging impact loads in gearbox bearings[7]. See Figs. 5 and 6.

Many types of drive systems in other equipment see severe transient loading and torque reversals without experiencing WEA damage to their bearings. Severe torque loads without reversals, and torque reversals that happen slowly in a controlled manner, would not create rapid plastic deformation in the bearing raceway. Wind turbines are different. Why? Their drive systems are unique in the severity of their torque reversals and the rapidity at which they can happen.

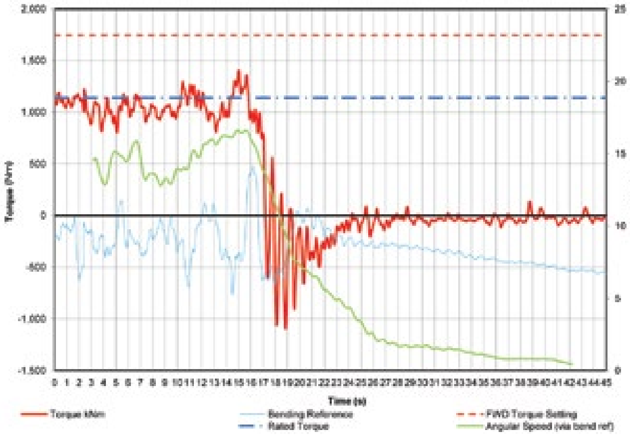

Fig. 5 – A Transient Torque Reversal (High Wind) event captured on a 2.0MW wind turbine.

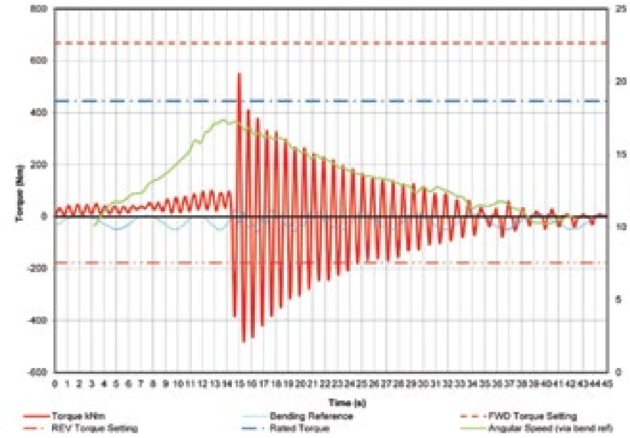

Fig. 6 – A Transient Torque Reversal (High Wind) event on 1.0MW wind turbine.

### Rapid Torque Reversals

What is it about a turbine drivetrain that causes it to be so susceptible to the rapid and severe torque reversals shown in Figs. 5 and 6? This has to do with the relative rotating masses (inertias) of the blades and the generator rotor, and how they can react against each other within the torsional natural frequency of the drive system. A typical turbine has 80 to 90% of its relative inertia in the blades, with most of the rest of the inertia in the generator rotor. In normal operation, the blades are driving the generator in the positive direction. A grid disconnect, emergency stop or high wind shutdown can trigger rapid aero braking of the blades that will attempt to decelerate the drive system. Most of the aero braking effort goes into decelerating the massive blade inertia, but some of it goes through the drive system to decelerate the generator. This typically causes a torque reversal in the drive system that can result in the inertias of the system winding up and unwinding against each other several times at the torsional natural frequency of the system as it decelerates. Note: the turbines of Figs. 5 and 6 have similar natural frequencies despite their significant size difference. How do these reversals cause impact loading in the bearings?

## Rapidly Reversing Bearing Load Zones & Impact Loads on Misaligned Rollers

Impact loads can be damaging to bearings in some other types of equipment and can even cause WEA damage. Rapidly reversing bearing load zones are also known to be very damaging to bearing life. During transient torque reversals every bearing in the gearbox sees a rapid load zone reversal of almost 180˚ that can cause severe impact loads between the rollers and the raceways. All the cited papers recognize that impact loading could be the source of the stress-induced subsurface WEA damage, and most of the papers name it as a suggested leading candidate.

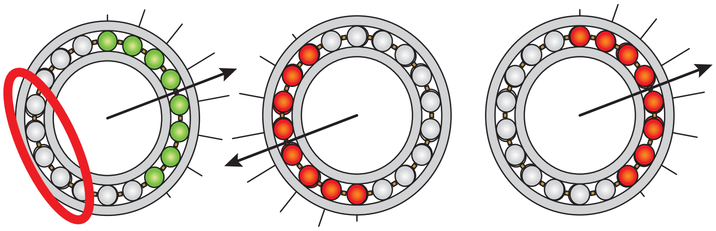

Fig. 7 Aligned rollers are in green load zone. Misaligned rollers are 180˚ opposite and are circled in red. In a TTR, these unaligned rollers are suddenly loaded repeatedly.

During normal operation, the rollers in the bearings are aligned and rolling at the expected speed while they are in the load zone. As they leave the load zone, the rollers slow down and can misalign within the tolerance of the cages. As they approach the load zone again, they are gradually brought back into alignment and smoothly accelerate to support the load. In a rapid load zone reversal, the unloaded rollers opposite the normal load zone are suddenly loaded while in this misaligned state. See Fig.7. This rapid loading increases the load concentration of the rollers in the middle of the inner race. See Fig. 8 for highest stress load locations.

## Blade Dynamics – Not All E-stops are the same…

### How Emergency Stops with High Winds, Turbulence, and Gusts Can Magnify Torque Reversals and Bearing Impact Loads

Pitchable blades allow today's wind turbines to achieve close to the ideal power curve shown in Fig. 10. Blade pitch control is important to maximizing the energy capture from the wind. In addition, it is critically important as the primary safety braking system for protecting the turbine from damaging wind loads and overspeed in the event of any turbine subsystem failure that prevents continued operation. Fig. 10 also shows the pitch angles of a typical modern turbine. At low wind speeds, the blades start out in a fully feathered position almost 90 degrees to the plane of the rotor swept area. In region II, the blades rotate to almost zero degrees pitch angle to extract the maximum power, capturing close to 50% of the wind's available power. In region III, the blades are pitched back to protect the turbine from high stresses as it strives to control and maintain full rated power. At cut-out speed, the blades are quickly pitched to provide braking to decelerate the turbine drive system.

The Fig. 11 view of the power curve masks the challenge of protecting the turbine from damage during high and turbulent winds. Fig. 14 shows the turbine power curve compared with the wind's available power. As the winds approach the typical cut-out speed of 25 mps (55 mph), the turbine may use less than 10% of the wind's available power. The blades must be pitched to the precise angle to effectively spill wind power equal to 10 times the turbine's rated power and protect the drive from excessive loads.

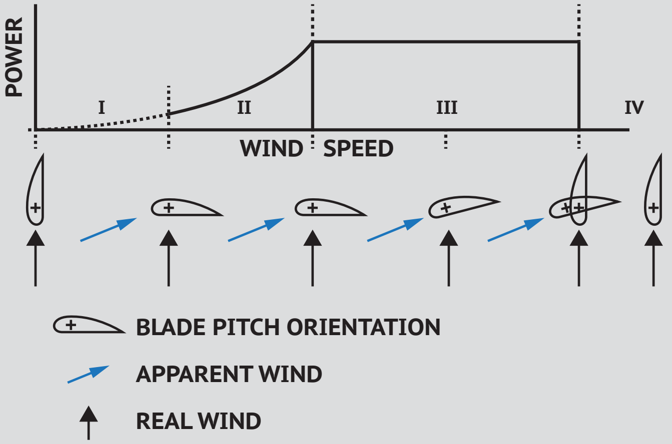

Fig. 10 – Typical Power Curve and pitch angles of modern wind turbines

With longer blades, the cut-in speed and the rated power speeds can be achieved at even lower wind speeds – dramatically improving the annual energy output and financial performance projections. But the excess wind power at cut-out speed that must be safely spilled over the edge of the blades may be even greater than 10 times the turbine's rated power.

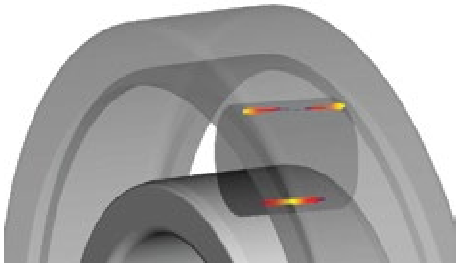

Fig. 8 – Image showing the areas in a bearing with the highest stress during a Transient Torque Reversal.

Although transient torque loads are common to many types of equipment, torque reversals of the magnitude and rapidity shown in Figs. 5 and 6 are unique to wind turbines. In gearboxes with helical gearing, every cylindrical bearing will see high axial loads simultaneous with the radial loads impacting misaligned rollers. See Fig. 9. These rollers may slip axially and damage the raceway surface, shortening bearing life through pitting and spalling. The sliding can also result in scuffing of the raceway causing microscopic cracks that allow subsurface entry of water or aggressive oil additives to initiate hydrogen induced WEA. If the radial impact load is so high that the roller breaks through the oil film, it can create mixed friction sufficient to prevent slipping axially. Axial subsurface stresses will be added to the Hertzian stresses from the radial impact, magnifying the stresses. The strain rate would be magnified, as well. If this exceeds a threshold where WEA microstructural alterations could form, it may explain why WEA damage is common in wind turbine gearboxes and rare in most other bearing applications. Tapered roller bearings can also be damaged by the effects of load reversals. High speed and intermediate speed bearings typically are not preloaded (due to thermal constraints) and see axial movement and impact loads.

Fig. 9 – Image showing the simultaneous radial impact and axial loading of the misaligned roller.

At high wind speeds, the blades are already pitched back in the range of 20-30 degrees to spill most of the wind power. During a grid loss or e-stop, the blades rapidly pitch further to decelerate the turbine. This is when the potential for torque reversals and impact loads to the bearings is the worst. The highest winds tend to occur during stormy weather when wind gusts and turbulence are high and the possibilities for grid loss and e-stops are greatest. High wind shutdowns and e-stops during gusty wind conditions can create a perfect storm for drive system torque reversals and damaging impact loads on the bearings. The worst torque reversals we have recorded occurred at high wind speeds. See Figs. 5 and 6.

**We are doing additional research and are gathering field data on how severely aerodynamic braking impacts the dynamics of the drivetrain. More to come on this subject.**

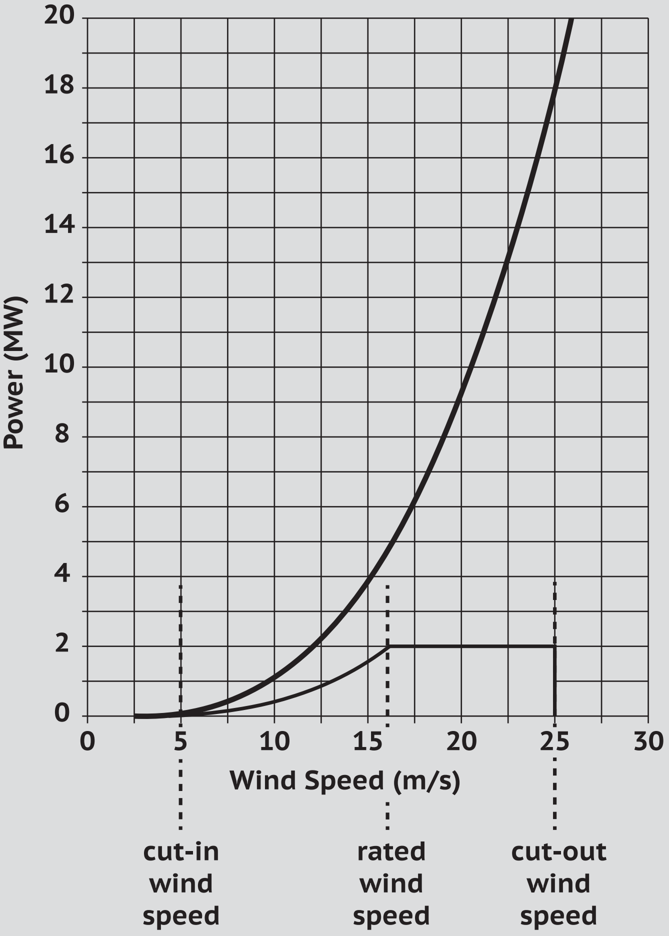

Fig 11 – Turbine power curve versus available wind

The bearing axial cracking issue did not become a prominent failure mode until the larger megawatt and multi-megawatt sized wind turbines began to dominate the market. The main gearbox failure mode of older, smaller wind turbines was not typically axial cracking. Their failure mode was primarily bearing surface deterioration from pitting and scuffing. Why has axial cracking developed as turbines have grown in size?

Fig.12 compares the relative torque magnitude and the rate of torque change during rapid reversals of three different sized turbine models. High resolution torque monitoring equipment recorded torque reversals that approximated the turbine rated torque at the high speed shaft on ¾ MW, 1 MW and 2 MW turbines. The torsional natural frequencies of the turbines during braking were all similar with oscillation periods about 0.75 second-per-cycle. The higher torque loads of the larger turbines can be accommodated in the sizing of the bearings but the oil film thickness will not increase. Any roller misalignment can more easily cause high local-contact stress during a torque reversal. The difference in the rate of increase of the reverse torque during the torque reversal may be an even bigger issue (comparison rate is noted in Fig. 12), as it directly relates to the strain rate in the raceway as the rollers impact. There is a threshold in rapid plastic deformation (adiabatic shear) where the instantaneous heat created causes the microstructural alteration of the base material. Could the increasing strain rate of larger turbines be exceeding that threshold? During rapid load zone reversals, could the rapidly increasing load on the rollers be creating fast enough plastic deformation to be transforming a microscopic sliver of the bearing steel to a super-hard ferrite WEA inclusion? Certainly all the elements for WEA microstructural alterations are present simultaneously for an instant. The torque reversal takes up the gear backlash and rapidly **impacts** the idling rollers on the unloaded side of the bearing. The misaligned rollers can make the stress concentration and the plastic deformation under the rollers worse and initiate mixed friction contact. Simultaneous reversal of the axial load on the bearing due to the helical gearing causes **surface traction** and additional stress at the inner raceway subsurface. The resulting **high strain rates and plastic deformation** can explain the creation of the WEA microstructural transformation.

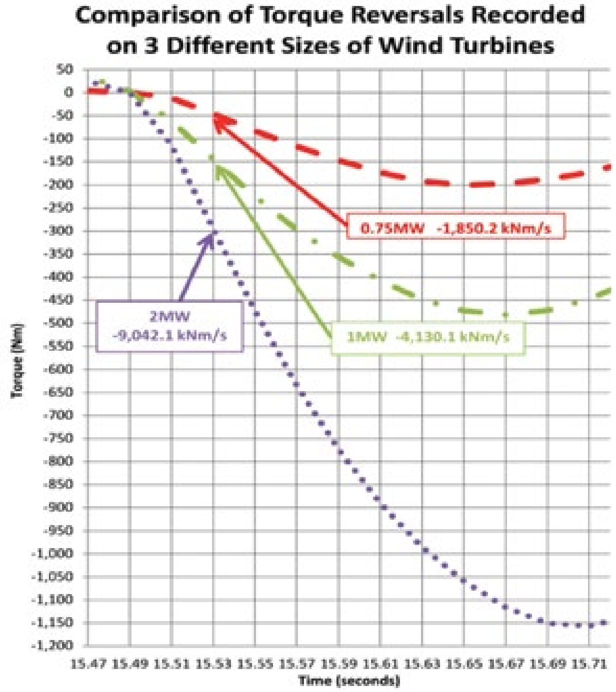

Fig. 12 – High resolution torque reversal recordings on 3 sizes of wind turbines showing the rate of change in torque. The steeper slope indicates significantly higher strain rates.

Because the WEA sliver is perfectly placed under the raceway surface, one microscopic sliver would be enough to initiate the WEA damage that would result in an axially cracked failed bearing. All it takes is one moment where the combination of high load and strain rate threshold is exceeded: one severe e-stop, a combination of an e-stop with a wind gust, high wind shutdown, control malfunction, sensor failure, etc. Some researchers have noted that torque reversals can create loads up to 2 ½ to 4 times nominal torque[4]. That would be 2 ½ to 4 times the torque loads shown in Fig. 12. Because the natural frequency is unchanged, the strain rate would be 2 ½ to 4 times higher, as well. Every doubling of the torque magnitude, with the same natural frequency, may effectively quadruple the instantaneous deformation energy that causes WEA damage.

## Conclusion

Rapid and severe impact loading of the rollers on the bearing raceway can cause stress-induced WEA damage, dramatically shortening the life of bearings and gearboxes. There are three ways to address the problem:

1. Strengthen the system or components to reduce the degree of damage by:
    - Changes in raceway material, processing and coatings;
    - Changes in bearing type;
    - Improved lubrication and oil additives;
2. Try to detect the damage and replace the bearings before catastrophic failure by:
    - More frequent borescoping;
    - Better conditioning monitoring systems;
3. Solve the root cause by preventing the excess stress and strain rate from happening by:
    - The addition of an asymmetric torque limiter;[7]

Ongoing research should prove the relative value of these solutions to extending bearing life. Some of the solutions proposed may incrementally extend life or prevent catastrophic failures with early detection of the axial cracks. The asymmetric torque limiter actually addresses the root cause – the rapid and severe loading that can initiate the stress-induced WEA damage. Simple frictional slip torque limiters are commonly used to protect wind turbine drive systems from severe torque overloads, such as generator short circuits. No evidence has been found that a basic torque limiter can provide protection against axial cracking. An asymmetric torque limiter has a much lower slip setting in reverse. Field testing of wind turbines with and without the asymmetric torque limiter has demonstrated its ability to significantly reduce the maximum reverse torque and rate of torque increase, thus reducing maximum stress and strain rate caused by the rollers impacting on the bearing raceway during the torque reversal. This approach would also dampen torsional vibrations to reduce the number of reversals. See Fig. 13. Field data from a 750 KW turbine (Fig 14) shows the effectiveness of the asymmetrical torque control in reducing the maximum reverse torque and the maximum rate of reverse torque increase. Note that both the magnitude of the stress and the maximum strain rate of the rollers impacting the raceway are reduced by over 50%; a 75% reduction of the instantaneous impact and deformation energy.

This deformation energy reduction can be achieved on larger turbines in a similar manner with the likely outcome of dramatically reducing the axial cracking. If asymmetric torque control can keep impact loads below the threshold where WEA microstructural alterations are initiated, super-hard WEA slivers could never form under the raceway, and axial cracks in gearbox bearings would cease to be a prominent mode of failure affecting the cost of wind turbine energy.

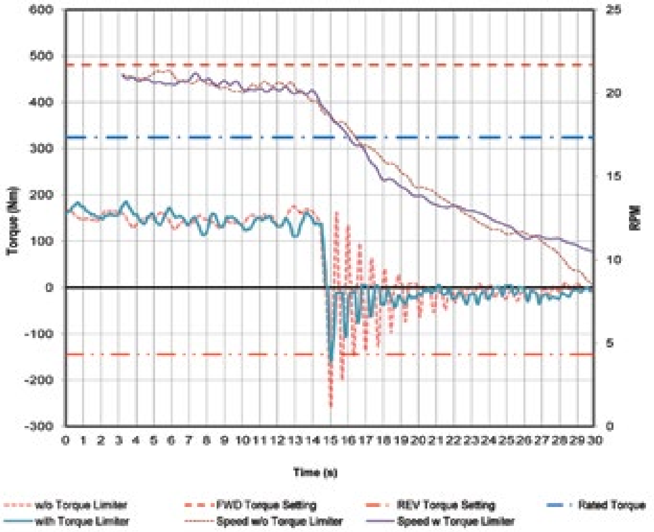

Fig. 13 – Dampening effect of reducing transient torque reversals to 40% of nominal torque.

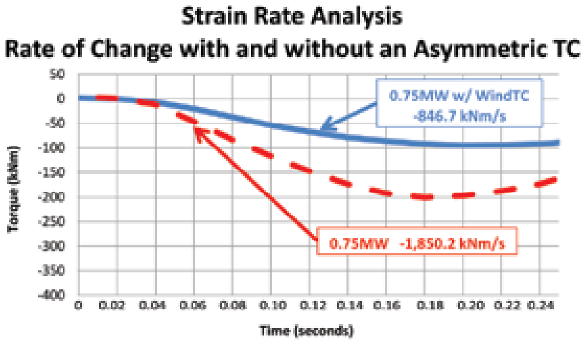

Fig. 14 - Comparison of torque reversal magnitude and rate of change for a 750 KW turbine with and without an asymmetrical torque control.

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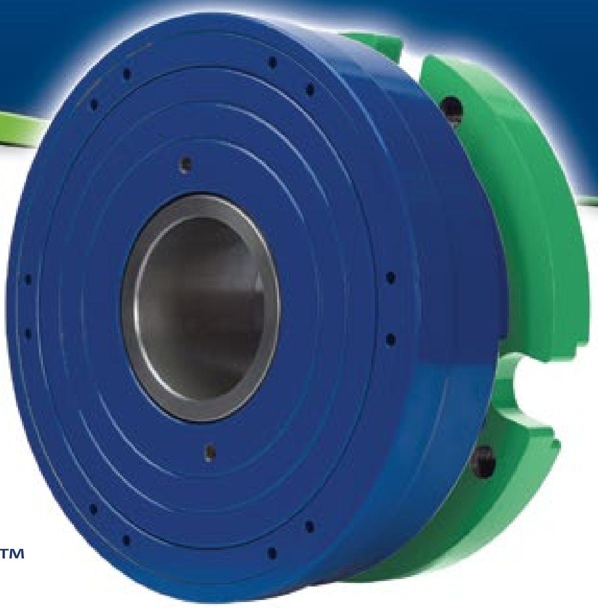

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