Wind Turbine Tribology Seminar

A Recap

Authors:
R. Errichello, GEARTECH
S. Sheng and J. Keller, NREL
A. Greco, ANL

Sponsors:
National Renewable Energy Laboratory (NREL)
Argonne National Laboratory (ANL)
U.S. Department of Energy

Presented at:
Renaissance Boulder Flatiron Hotel
Broomfield, Colorado, USA
November 15-17, 2011

Table of Contents

List of Tables

Foreword

Tribology is the science and engineering of interacting surfaces in relative motion. It includes the study and application of the principles of friction, lubrication, and wear that impact the design and operation of bearings and gears in wind turbine gearboxes, and their subsequent maintenance requirements and overall reliability. The Wind Turbine Tribology Seminar was convened by the National Renewable Energy Laboratory (NREL), Argonne National Laboratory (ANL), and the U.S. Department of Energy (DOE) to explore the state-of-the-art in wind turbine tribology and lubricant technologies, raise industry awareness of this complex topic, present the science behind the technologies, and identify possible R&D areas for improvements. The Wind Turbine Tribology Seminar was held at the Renaissance Boulder Flatiron Hotel in Broomfield, Colorado, on November 15-17, 2011. This report is a summary of the seminar and its conclusions.

The presentations given at the meeting can be downloaded at:

http://www.nrel.gov/wind/pdfs/2011_wind_turbine_tribology_seminar.pdf

Interested readers who were not at the meeting may wish to consult the detailed publications listed in the bibliography section, obtain the cited articles in the public domain, or contact the authors directly.

Acknowledgements

The Wind Turbine Tribology Seminar was organized by a small committee, but its value resulted from the contributions of many. The concept of the workshop is credited to Brian McNiff (McNiff Light Industry). Brian and Bob Errichello (GEARTECH) used their long standing experience in the field of wind turbine gearbox failure analysis and contacts among world class experts to suggest both the format of the seminar and most of the speakers. We are deeply indebted to them for their contributions, not only for this seminar, but also their continuous contributions to wind turbine gearbox reliability.

Aaron Greco (ANL) provided additional perspective on the subject of tribology and suggested additional world class experts. Aaron also guided the seminar's organization, collaborated on the technical content, and contributed to this report.

Shawn Sheng and Jonathan Keller (NREL) provided the organizational and logistical planning aided by the previously mentioned contributor's technical insight.

Each of the speakers is a recognized expert who brought various perspectives from the tribology field and how each affects wind turbine reliability.

The organizers express their deepest thanks for the efforts of all the contributors.

Introduction

Surface damage and failure of contacting components (i.e., bearings, and gears) are among the more frequent and costly types of failures for a wind turbine and can be the root cause of system failure for the gearbox, main rotor bearing, generator, yaw system, and blade pitch systems. Understanding the fundamental tribological factors that influence contacting element performance is important to addressing these issues; disseminating this information to foster collaboration on this topic is one of the main objectives of the 2011 Wind Turbine Tribology Seminar. The other objective is to identify the major tribological related issues impacting the wind energy industry leading to recommendations for future research and development strategies to improve turbine reliability and ultimately lower the cost of wind energy.

The Wind Turbine Tribology Seminar was conceived to: (1) present state-of-the art tribology fundamentals, lubricant formulation, selection of oils and greases, gear and bearing failure modes, R&D into advanced lubricants, and mathematical modeling for tribology, and field observations; (2) provide a forum for researchers, tribologists, lubricant engineers, wind turbine manufacturers, gearbox manufacturers, bearing manufacturers, owners, operators, and those in the supply chain to share their knowledge and learn from their colleagues; and (3) develop a list of R&D needs to guide future wind turbine tribology research.

The seminar consisted of six sessions with 29 moderators, speakers, and panelists. Three came from Germany, two from the UK, one from Belgium, and one from Japan. About 110 attendees attended the seminar and participated in the discussions. Table 1 details the seminar's agenda. The next section summarizes each presentation, and final section presents conclusions. Appendix A contains the speakers' biographies.

Table 1. Seminar Agenda

Day 1: November 15, 2011		
Time	Topic	Speaker and Affiliation
8:00 AM	Introduction	Paul Veers, NREL Ali Erdemir, ANL
8:30 AM	Tribological Challenges in Wind Turbine Technology	Gary Doll, U of Akron
Session I: Tribology Fundamentals (Bob Errichello, GEARTECH)		
10:00 AM	Elasto Hydrodynamic Lubrication (EHL) Fundamentals	Vern Wedeven, Wedeven Associates
11:00 AM	EHL Surface Interactions in Micropitting	Pwt Evans, Cardiff University
1:00 PM	The Influence of Lubricant Properties on EHL Film Thickness and Traction	Andy Olver, Imperial College
2:00 PM	Surface Roughness and Micropitting	Lane Winkelmann, REM Surface Engr
Session II: Lubricant Fundamentals (Bill Herguth, Herguth Laboratories, Inc.)		
3:00 PM	Fundamentals of Lubrication Gear Oil Formulation	Jon Leather, Castrol
4:00 PM	Selecting Synthetic Gear Oil	Dennis A. Lauer, Klüber Lubrication
5:00 PM	Wind Turbine Grease Lubrication	Henri Braun, ExxonMobil

Day 2: November 16, 2011		
Session III: Wind Turbine Tribological Damage (Shawn Sheng, NREL)		
8:00 AM	NREL Gearbox Reliability Collaborative Failure Database Project	Mark McDade, NREL
8:30 AM	Bearing and Gear Failure Modes Seen in Wind Turbines	Bob Errichello, GEARTECH
10:00 AM	Microstructural Alterations in Hertzian Fatigue	Bob Errichello, GEARTECH Andy Olver, Imperial College
11:00 AM	Classic Bearing Damage Modes	Ryan Evans, Timken
Session IV: Root Cause Hypotheses (Brian McNiff, McNiff Light Industry)		
1:00 PM	Introduction	Bob Errichello, GEARTECH
1:15 PM	The Mechanism of White Structure Flaking in Rolling Bearings	Hideyuki Uyama, NSK
2:15 PM	The Bearing Axial Crack Root Cause Hypothesis of Frictional Surface Crack Initiation and Corrosion Fatigue-Driven Crack Growth	Jürgen Gegner, SKF
3:45 PM	Hammering Wear Impact Fatigue Hypothesis	Johan Luyckx, Hansen
5:00 PM	Influence on Bearing Life by New Material Phenomena	Walter Holweger, Schaeffler

Day 3: November 17, 2011		
Session V: R&D Activities (Jim Johnson, NREL)		
8:00 AM	Surface Treatment and Nano Lubricant	Ali Erdemir, ANL
8:45 AM	Novel Macromolecular Nano Lubricant Oils and Greases	Ajay P. Malshe, NanoMech Inc.
9:45 AM	Update on the Development of a Full Life Wind Turbine Gearbox Lubricating Fluid	Manfred Jungk, Dow Corning
10:30 AM	Modeling Tribological Contacts for Wind Turbine Gearbox Component Life Prediction	Nathan Bolander, Sentient
11:15 AM	Approaching Component Surface Fatigue Life by Integrated Contact and Lubrication Mechanics & Beyond	Jane Wang, Northwestern Univ
Session VI: R&D Needs Development (Aaron Greco, ANL)		
1:00 PM	Panel Discussion: Field Observations of Tribological Damage in Wind Turbines A look at Wind Turbine Oil Over Time Damage Seen From a Wind Turbine Manufacturer's Angle Pitch and Yaw Bearing Damage	 Art Miller, enXco Bill Herguth, Herguth Labs Shawn Doner, Winergy Les Miller, Kaydon
2:30 PM	Future R&D Areas	All Attendees
3:30 PM	Tour of National Wind Technology Center	Jim Johnson, NREL

Critical evaluation of the seminar's information revealed the complex challenge of tribology for the wind industry and highlighted the need for multidisciplinary research in areas including contact mechanics, tribology, materials science, lubrication, mechanical engineering, component design, condition monitoring, and modeling.

Summary of Presentations

Introduction

Wind Market and NREL Gearbox Reliability Research Overview

Paul Veers, NREL

The presentation began with an overview of the wind turbine assets at NREL and the wind energy market globally and in the United States and then segued into a discussion of wind turbine gearbox reliability challenges. The need for improved reliability in terms of failure frequency and resulting downtime in wind turbine drive trains, including the main shaft/bearings, gearbox, and generator, was demonstrated. An overview of the Gearbox Reliability Collaborative (GRC), including tests, modeling, analysis, overhaul database, and condition monitoring was presented along with drive train testing assets at the National Wind Technology Center (NWTC).

Argonne National Laboratory (ANL) Wind Tribology Overview

Ali Erdemir, ANL

An overview of ANL's tribological, surface treatment, and nano-lubricant research and its engineering staff was presented. Argonne's tribology mission is to perform leading-edge R&D in the fields of materials, lubricants, surface engineering, and tribology to:

- Improve efficiency, durability, and reliability of machine components that operate under severe tribological conditions (including those in wind turbines)
- Understand fundamental tribological mechanisms through advanced surface/structure analytical methods and modeling/simulation.

Argonne tribology strengths, facilities, and recent success stories, such as super-hard nano-composite coatings and carbide-derived carbon, were discussed. Current wind turbine R&D activity in ultra-fast boriding and nano-boron additives were presented. Future areas of R&D, such as explaining the root causes of failure mechanisms, commercial implementation of advanced surface technologies, and investigation of hydrogen embrittlement were discussed.

Tribological Challenges in Wind Turbine Technology

Gary Doll, University of Akron

Some wind turbine bearings are not achieving their desired operational lives because of life limiting wear modes. Tribological issues manifest themselves through different bearing failure modes in various systems of wind turbines. The primary mechanisms in pitch/yaw bearings, main shaft bearings, the gearbox, and the generator are false brinelling, micropitting, wear and cracking, and electrical arc damage. Micropitting and smearing are caused by large amounts of roller/raceway sliding in situations in which lambda (Λ), the ratio between the oil film thickness and the combined surface finishes of the parts, is low. Micropitting, smearing, and false brinelling problems can be solved with durable tungsten carbide-reinforced, amorphous, hydrocarbon thin film (WC/aC:H) coatings on rollers. WC/aC:H coatings on rollers provide bearings with a high tolerance of debris damage. The solutions to micropitting and scuffing in gears are the same as in roller bearings. The root cause of radial cracking and wear from an

Irregular White Etch Area (IrWEA) is controversial, but probably mechanical in nature. Cleaner steels, higher compressive stresses on raceways, increased Λ, and less roller skidding can reduce IrWEA wear and radial cracking, if the IrWEA wear is of mechanical origin. In generators, less electric arc damage is shown in oils than in greases. Examples of problems without current solutions are: 1) increasing seal life and 2) the development of a common nacelle lubricant.

Presentation Summary

- Wear problems in pitch and yaw bearings
    - False brinelling because bearings and gears are not rotating, vibrations cause small motions termed dither. This leads to fretting.
    - Fretting leads to false brinelling and fretting corrosion
    - There is a critical dither angle
    - False brinelling is avoided by regular rotation, along with adequate base oil viscosity and antiwear additives
- Wear problems in main shaft bearings
    - Micropitting defined
        - Surface initiated fatigue due to roller/raceway sliding and low Λ condition (oil film thickness)
        - Uneven load distribution between upwind/downwind bearing rows
        - Micropitting avoidance through reduction of roller/raceway sliding by using preloaded tapered roller bearings will reduce risk of micropitting and/or coatings and super-finishes on SRB rollers reduce shear stresses and increase Λ by polishing raceways in operation
- Wear problems in gearbox
    - Scuffing wear
        - Rollers skidding across raceway in low Λ condition generates local temperatures high enough to melt steel
        - Caused by decreasing loads and transient conditions
        - Avoid transients and reduce clearance, or use coated rollers
    - Axial Cracking & Wear from IrWEA
        - Caused by hydrogen embrittlement or mechanical causes such as scuffing
        - Avoidance through black oxide on rings and rollers, usage of case carburized rings from ultra clean steel, and reduction in shear stress (pre-loaded TRBs and coatings)
    - Debris Damage
    - Gear scuffing
- Electric Arc Damage in Generator
    - Loads generated during grid reversal
    - Avoidance through usage of ceramic balls, electrical insulating coating on rings, use of oil instead of grease, and usage of dry oils with high dielectric strengths.

Tribology Fundamentals

Elastohydrodynamic Lubrication (EHL) Fundamentals

Vern Wedeven, Wedeven Associates, Inc.

The formation of an elastohydrodynamic (EHD) film to provide elastohydrodynamic lubrication (EHL) is the key lubrication mechanism for long-life and robust operation of rolling element bearings and gears for wind turbines. Understanding the EHL mechanism, and how it uniquely links to theory, provides a foundation for engineering design, tribology technology development, and problem solving. The performance of EHL films is linked to fundamental and inherent lubricant properties of viscosity, pressure-viscosity coefficient, and traction coefficient. Seven features characterize this mechanism and spell the acronym, MIRACLE:

M = Molecular attraction of adsorbed films, which drags lubricant along with the moving surfaces

I = In-flight refueling by fluid flow in the converging inlet region, in which the surfaces supply fluid and pump up the film

R = Radical increase of viscosity with pressure, in which the oil becomes a pseudo-solid

A = Accommodation of stress by elastic flattening of surfaces and by the pseudo-solid, which rides the Hertzian region

C = Cushioning of asperities due to asperity deformation

L = Limiting shear strength of pseudo-solid film, which limits traction forces

E = Exit without trauma, in which the pseudo-solid reverts to oil without damage

Wind turbine operational features, including start/stop, present unusual demands and limitations for EHL mechanisms to be operational. The linkage between EHL mechanisms and boundary lubrication mechanisms is essential for understanding bearing/gear performance limits and failure mechanisms. Five key tribology parameters (entraining velocity, film thickness-to-surface roughness ratio, sliding velocity, total contact temperature, and contact stress) are used to "manage" technology development for the lubricated contacts of bearings and gears. These parameters can be used for design, failure analysis, lubricant formulations, and evaluation of materials and surface engineering technologies. Specialized testing illustrates how controlling lubrication and failure mechanisms are expected to play out in service hardware.

EHL Surface Interactions in Micropitting

Pwt Evans, Cardiff University, UK

The presentation detailed the effect of surface roughness on Elastohydrodynamic Lubrication (EHL). The importance of surface roughness was discussed in terms of Λ. The importance of surface roughness was illustrated for cases with sub unity Λ in the extreme loading events that occur due to the interaction of surface asperity features. The application of suitable analysis methods to gear contacts operating in these conditions shows that their operation occurs in a mixed lubrication regime, with direct surface interaction of the asperity features occurring as transient high pressure events.

High pressure events, such as asperity interaction, can lead to scuffing failure when the asperity contact levels are high. They also lead to cyclic asperity loading within the EHL contact due to sliding effects. Cyclic loading is used as an input to fatigue calculations that identify the near surface zone beneath heavily loaded asperities and have high probabilities of fatigue failure. The manner by which these asperities are subjected to plastic deformation during the running-in process, and the resulting residual stress field, was considered.

Effect of Lubricant Properties on EHL Film Thickness and Traction

Andy Olver, Imperial College, UK

The presentation discussed the effects of various phenomena on film thickness and traction. Dimensionless speed, and material and load parameters were defined and basic regression equations to estimate the film thickness were presented. Methods to estimate the effect of temperature on lubricant viscosity were discussed. The phenomenon of “shear thinning," defined as the variation of viscosity with shear rate, was shown. The Ree-Eyring versus Carreau methods for estimation of the coefficient of friction were discussed, including accounting for the slide roll ratio and temperature droop as measured in simple bench tribometer tests. The following are proposed:

- A protocol for extracting a description of the EHL traction behavior of an oil from simple bench tribometer tests
- This can be used in conjunction with a coupled thermal EHL model to predict traction over a wide range of conditions for competing oils.

Surface Roughness and Micropitting

Lane Winkelmann, REM Surface Engineering

The presentation discussed typical wind turbine failure modes, and described the basics of micropitting on gears. The benefits of super-finishing gears were discussed. Super-finishing modifies the topography of the gears and can eliminate micropitting, increase lubricant life and cleanliness, and increase component life. It is relatively easy to implement. Isotropic super-finishing, in which directionally-oriented grinding asperity rows are eliminated, was discussed in detail. Isotropic super-finishing can reduce the mean roughness value by an order of magnitude while maintaining the overall component geometry. Supporting validation work and the results from micropitting tests through standard methods for Forschungsstelle für Zahnräder und Getriebebau (FZG) Brief Test of Grey Staining (BTGS) was shown. The current status of implementation of isotropic super-finishing was discussed.

Lubricant Fundamentals

Fundamentals of Lubrication Gear Oil Formulation

Jon Leather, Castrol Industrial

The presentation discussed a systematic approach to gear oil formulation and development, starting with the fundamentals of gear oils and their application in wind turbines. There are industrial and wind industry requirements for gear oils. The composition, effects and side-effects of gear oils and their components is a balancing act when formulating the oils. An example project was discussed that demonstrated the basic process of building a new product. Once a prototype is developed, field trials occur through the final development stages.

The challenges facing wind turbine gear oil formulation are manifested by the requirements for wind turbine operation:

- Long oil life: +3 to 5 year minimum
- Use of anti-scuff/antiwear additives with high load carrying capacity
    - Wear performance should remain constant as the oil ages
    - Micropitting protection
- Oil cleanliness: 16/14/11 for new oil 18/16/13 used
- Wide temperature range
    - Cold startup
    - High operating temperatures
- Oxidation stability
    - Resistance to sludging
    - No effect on the service intervals of filters
- Stability with water and condensation: Rust and corrosion protection

Other requirements by gearbox and wind turbine manufacturers include:

- Deutsches Institut für Normung (DIN)-minimum requirements
- Compatibility with elastomers and paints
    - Static and dynamic tests
    - Long-term tests with a duration of at least 1000 hrs
- Foam tests
    - Mixed with anti-corrosion oil
    - After filtration
- FZG-tests

  - Micropitting tests
  - Increased loads and/or tests without running in
- Tests of antifriction bearings:
  - Corrosion protection, especially salt water
  - Formation of residues under the influence of water and temperature
  - Wear tests on an FE 8 test-rig
  - Endurance tests on test benches for antifriction bearings
- Further requirements
  - Filterability
  - Good cleanliness class and automatic countability (ISO 4406 Particle Count)

Selecting Synthetic Gear Oil

Dennis A. Lauer, Klüber Lubrication

When selecting synthetic gear oil, the maximum performance level that the gear oil is able to meet should be compared to the actual performance of the gear oil. The maximum performance of gear oils, with advanced additive packages, and the impact of the base oil on performance parameters were summarized. Over the life cycle of the turbine, the highest performance oil proves to be the most cost effective, though it commands the highest price.

The requirements for wind turbine gear oil are higher than the industrial gear oil requirements specified by DIN 51517-3. Specifically, wind turbine gear oil is expected to meet the following requirements:

- High scuffing and micropitting load-carrying capacity
- Low friction behavior
- No negative influence on wear behavior and life time of rolling bearings
- High oxidation stability
- High upper operating temperature
- No residue formation
- No negative influence on radial shaft seals.

When selecting wind turbine gear oil, the following performance characteristics should be considered:

- Scuffing load-carrying capacity greater than LS 13
- Resistance to micropitting greater than, or equal to, LS 10
- Pitting load-carrying capacity

- Bearing load-carrying capacity
    - Suitable for rolling bearing lubrication FAG FE8 test
    - Maximum roller wear <= 10 mg, maximum cage wear <= 100 mg
- Foam test
- Elastomer compatibility
    - Static elastomer compatibility, according to DIN ISO 1817
    - Dynamic elastomer compatibility, according to DIN 3761
- Oil change intervals
- Viscosity-temperature behavior
- Efficiency, oil temperature, wear, and wear rate
- Friction behavior.

Wind Turbine Grease Lubrication

Henri Braun, ExxonMobil

Lubricating greases face a demanding environment in wind turbine applications. Wide operating temperature ranges, shifting wind forces and directions, high torques and loads, water contamination, and boundary lubrication conditions are the key performance challenges. These are exacerbated by the operator's desire to minimize the number of greases used and to maximize re-greasing intervals. Thus, developing lubricating greases for wind turbines is a costly and complex undertaking that must consider numerous, often conflicting, targets. Synthetic-base oils can help meet the lubrication needs of main pitch and yaw bearings with one grease, and help reduce traction and extend grease life. Still, achieving optimum performance requires a carefully balanced formulation of base oil, thickener, and additives. Finally, extensive laboratory, bench, and field testing is necessary to demonstrate overall performance.

The challenges facing wind turbine grease formulation are demonstrated by various and conflicting requirements across different turbine components as follows:

- Main bearing
    - Fluctuating winds introduce thrust loads
    - High load and slow speed make EHL conditions difficult to achieve; suggest the use of high viscosity base oils (ISO VG 460)
- Pitch bearing
    - High torques and bending moments during rotation
    - Bi-directional oscillation (partial rotation) results in boundary lubrication conditions
    - Vibration leads to fretting wear and corrosion

- Yaw bearing
    - High thrust loads from weight of nacelle
    - Bi-directional oscillation (partial rotation) results in boundary lubrication conditions
    - Vibration leads to fretting wear and corrosion
- Yaw gears
    - Vertical tooth flanks require excellent adhesion
    - Exposure to environment necessitates excellent corrosion protection
- Generator bearing
    - Moderate to high speed rotation
    - Lower base oil viscosity than pitch, yaw, and main bearings (ISO VG 100)
    - NLGI 2 or firmer, with good oil release control

To address these challenges, synthetic oil greases are advantageous over mineral oil products, providing:

- Wider operating temperature range, lower viscosity at low temperatures and higher viscosity at high temperatures
- Lower traction, reducing heat generation and energy losses
- Longer grease life

As is the case for wind turbine gear oil development, the development of wind turbine grease also is a costly and complex undertaking that requires:

- Consideration of numerous, often conflicting, targets
- Extensive laboratory, bench and field testing to demonstrate performance

Two attempts to address these challenges include:

- Main bearing protection through a balance of EHL and additive chemistry
- Pitch and yaw bearing protection through targeted additives and controlled bleed

Wind Turbine Tribological Damage

NREL Gearbox Reliability Collaborative Failure Database Project

Mark McDade, NREL

The four parts of the NREL Gearbox Reliability Collaborative were explained and include modeling and analysis, testing, condition monitoring, and the failure database. The GRC Failure

Database was presented in detail, including its value to industry and individual participants and demonstrating the actual software used to input information resulting from gearbox overhauls. The database houses information collected from gearbox rebuilds, such as:

- Background data from in-field operation
- Failure modes from tear-down inspection
- Existing data from records.

The goal of the database is to share "sanitized data" within the participating group and to identify the root cause of failures and prescribe remedies. The database software provides a structured data collection system with a navigation tree that is visually-oriented. It offers wireless image transfer from the camera to the software. To expedite data input, the database software includes embedded models of each gearbox, a failure atlas with classifications of failure modes, and interactive help. Reports are automatically generated that identify:

- The failure location
- Failure images, with comments from the inspector
- Failure mode identification and description.

Bearing and Gear Failure Modes Seen in Wind Turbines

Robert Errichello, GEARTECH

Wind turbine bearings and gears have a long history of failure modes such as Hertzian fatigue, consisting of macropitting, micropitting, or subcase fatigue, and by scuffing or bending fatigue. Current failures of rolling-element bearings in wind turbine gearboxes are manifested as axial cracks in the inner rings. Current failures in gears are manifested as bending fatigue that originate from non-metallic inclusions. Examples of bearing and gear failures were presented to demonstrate the morphology of the various failure modes. Current failure modes that are prevalent in wind turbine gearboxes include:

- Bending fatigue, originating from non-metallic inclusions
- Micropitting, due to rough surfaces or lubricants with inadequate micropitting resistance
- Subcase fatigue, due to grind temper or inadequate case depth
- Adhesion or abrasion, due to contaminated lubricants
- Fretting corrosion during parking
- Case/core separation, due to excessive case depth at tips of teeth
- Axial cracks in bearing inner rings.

Microstructural Alterations in Hertzian Fatigue

Robert Errichello, GEARTECH

Microstructural alterations in Hertzian fatigue have been studied for decades and are a key indicator for the fatigue mechanism in rolling-element bearings and gears for wind turbines. Several features were described that characterize microstructural alterations such as: butterflies, dark-etching areas (DEA), white-etching areas (WEA), flat white bands, and steep white bands. Microstructural alterations were shown to be linked to Hertzian stress and the number of load cycles.

Current failures of rolling-element bearings in wind turbine gearboxes are manifested as axial cracks in the inner rings. The white-etching areas associated with this failure mode are irregular and are termed irregular white-etching areas (IrWEAs) or white-etching cracks (WECs). Several theories have been proposed for the root cause of IrWEAs, WECs, and axial cracks. However, none of the theories have been proven, and it is an active field of research.

- It is probable that IrWEAs and WECs have identical driving mechanisms that manifest as different alterations in bearing microstructure depending on the specific metallurgy of the material's alloy and processing.
- How IrWEAs and WECs develop and progress is not understood yet. Both have been characterized as brittle fracture modes that generate cleavage fractures. It might be a single-step or a multiple-step process that generates cleavage cracks and white-etching bands.
- It is not understood how coatings, such as black oxide, help to prevent axial cracks. They might reduce traction stresses, damp vibrations, or prevent diffusion of hydrogen. On the other hand, the temperatures used to coat the components might beneficially alter the bearing metallurgy.

Microstructural Alterations in Rolling Contact

Andy Olver, Imperial College, UK

Transformations, at inclusions and on crack faces, are indistinguishable from those occurring at the surface in simple rubbing experiments (e.g., fretting). Crack faces in rolling contact are subject to fretting displacements and high pressure. Surface cracks are typically associated with local plastic deformation due to reduced plastic constraint. The resultant residual stresses control the direction of small surface cracks. Microstructural alterations in Hertzian contacts have the following features:

- Transformations at inclusions and on crack faces are indistinguishable from those occurring at the surface in simple rubbing experiments (e.g., fretting)
- The alterations are nano-grained ferrite (e.g., cell ferrite)
- Crack faces in rolling contact are subject to fretting displacements and high pressure
- Surface cracks are typically associated with local plastic deformation, due to reduced plastic constraint

- Resultant residual stresses control the direction of small surface cracks.

Classic Bearing Damage Modes

Ryan Evans, The Timken Company

Rolling element bearing damage in the field is attributable to either material fatigue, or wear, in most applications. Bearing life prediction tools estimate the statistical likelihood of contact surface spalling due to material fatigue, given a set of assumptions about the bearing operating conditions. However, even if a bearing is designed, manufactured, and specified for an application, premature damage and wear may occur due to contamination, inadequate lubrication, and/or misuse. Classic examples of these damage modes and their causes were presented for steel rolling element bearings. In addition, transmission electron microscopy characterization of subsurface microstructural alterations, called “white etch areas,” from wind turbine gearbox bearings was discussed. Classic failure modes include:

- Macropitting (spalling)
    - Inclusion origin
    - Point Surface Origin (PSO)
    - Geometric Stress Concentration (GSC)
- Micropitting (peeling)
- Wear or other damage
    - Abrasive wear
    - Debris denting
    - Etching/corrosion
    - False Brinelling/Fretting corrosion
    - True Brinelling
    - Heat discoloration
    - Scuffing (smearing)
    - Electric discharge

Investigations are underway to better understand WEA microstructural alterations and their causes.

Root Cause Hypotheses

The Mechanism of White Structure Flaking in Rolling Bearings

Hideyuki Uyama, NSK, Japan

Microstructural change is observed on cross sections of the rolling bearings used for wind turbine gearboxes. This microstructural change is the same phenomena, called a "white structure." NSK has experienced premature flaking, due to white structures in bearings, in automotive electrical accessories, as an example. The main cause of white structures is due to hydrogen generated by decomposition of the lubricant. Formation mechanisms of white structures related to hydrogen embrittlement, and accelerating factors of hydrogen generation, were reported. Our research shows the following:

- Bearing failures in wind turbine gearboxes may be classified as white structure flaking
- White structure flaking is induced by hydrogen that diffuses into the bearing's steel
- White structures are caused by localized, microstructural changes. The presence of white structures indicates that hydrogen-induced, localized plastic deformation is present in rolling contact fatigue
- The type of lubricant, slip, static electricity, and material influence white structure flaking.

It is hoped that our experience with automotive bearings will help solve wind turbine bearing failures.

The Bearing Axial Crack Root Cause Hypothesis of Frictional Surface Crack Initiation and Corrosion Fatigue-Driven Crack Growth

Jürgen Gegner, SKF, Germany

Results of failure analysis and research were presented. Some medium and large size bearings, such as those used in wind turbine gearboxes, suffer from premature failures due to axial raceway cracks. Root cause hypotheses from the literature were reviewed. Surface initiation, and the subsequent chemically-assisted propagation of the cracks, occurs as brittle spontaneous fracture and corrosion fatigue, respectively. Local microstructural changes result from hydrogen impacts due to aging reactions of the lubricant at the tip and the rubbing faces of the advancing crack. Material response in the form of cleavage-like surface cracking suggests there are causative tangential tensile stresses. Weaker areas with inhomogeneities and edge-zone embrittlement were considered. The tensile stresses are caused by sliding friction in the rolling contact, induced by vibrations, for example. A tribological model was presented. The tangential tensile stresses are estimated to be high enough for cracking. A combination of cold working, because it generates compressive residual stresses, together with black oxidizing and final low-temperature reheating, is proposed as an effective countermeasure. Our conclusions are:

- Axial cracks initiate from the surface by brittle, spontaneous, cleavage-like fractures
- The root cause of the axial cracks is tangential tensile stress, due to high local sliding friction
- Surface cracks propagate by corrosion fatigue cracking (CFC)
- CFC is caused by lubricant decomposition at the crack tips and on the rubbing crack faces.

Hammering Wear Impact Fatigue Hypothesis

Johan Luyckx, Hansen Transmissions, Belgium

The main features and status of the WEC/IrWEA failure mode in roller bearings applied in wind gear units were described. The material observations in WEC/IrWEA were shown and a detailed interpretation concludes that different material damage patterns are generated by an impact load system. The updated Hansen wind experience regarding WEC/IrWEA failures was presented. It detailed bearing variants that have improvement potential. The material research performed on the different drivers identified in the Hansen wind experience were discussed and interpreted. These resulted in the formulation of a root cause hypothesis. There is an observed correlation between WEC/IrWEA failed raceways and the hammered (flattened) appearance of the raceway. The hypothesis is that the impact load system is caused by a roller contact on a flattened wear particle from the raceway, henceforth called "hammering wear impact." This impact load system generates subsurface material damage, which initiates a bearing fatigue failure process. Further research work is proposed and a summary of all potential solutions and parameters was presented with the following conclusions:

- Axial cracks are caused by the impact load system
- IrWEAs and WECs are consequences of the impact load system
- Countermeasures include:
    - Raceway surface treatment, such as reduced roughness, black oxide, hot assembly, strain hardening, hard coatings
    - Case carburizing

Influence on Bearing Life by New Material Phenomena

Walter Holweger, Schaeffler

Classical failure modes in bearings appear as a subsurface dark etching area, followed by strictly-oriented low and high angle white bands (LAB/HAB). The appearance of such features is a function of pressure and is expressed in the Woehler line. In contrast to this classical fatigue, irregular white etching bands indicate a new fatigue process not ruled by the classical theorems (the Woehler Line). A majority of failures occur in wind mill applications, in the high speed shaft at low nominal contact pressure.

Detailed forensic investigations show the degradation of the matrix and the matrix carbides in a nanometer scale. Downsizing implies the presence of a severe plastic deformation mode, normally found in high pressure torsion experiments. Neither severe plastic deformation nor high pressure torsion is found in the real application.

Test rigs at Schaeffler technologies prove the occurrence of irregular white etching with respect to loading and materials. Those results show that IrWEAs occur due to multiple influences, e.g., vibrations, straying currents, and the chemistry of lubricants and preservatives. Recent results prove lubricants and preservatives to be of major importance, while vibrations, straying currents, and mechanical loading are of minor importance.

A stringent model of irregular white etching area requires a multiple descriptor model. The hierarchy of root causes is:

- Nature of EHL lubrication (preservatives, additives)
- Nature of the surfaces (dark oxide, hot assembly, passivation)
- Nature of the material (type of heat treatment, microstructure, interstitials)
- Nature of the loading (vibration, slip, electric discharge)

R&D Activities

Surface Treatment and Nano Lubricant Bearings

Ali Erdemir, ANL

Leveraging over 25 years of tribology experience (specifically, surface engineering, advanced lubricants, materials and coatings, and surface analytical characterization), the Argonne tribology group has been active in the wind turbine area for several years. The objective of the current work has been to develop, test, and implement innovative surface engineering and nano-lubrication technologies that can increase the reliability of wind turbine drivetrain components; primarily through an ultra-fast boriding process, lubricant- derived, diamond-like carbon (DLC) coatings, and nano-boron lubrication technology.

The ultra-fast boriding process was developed to enhance the hardness of gear and bearing surfaces, by more than a factor of two, compared to standard carburizing (1800 HK to 600 HK). This was achieved through an advanced electrochemical process that increases efficiency by 80% compared to current boriding, making it economically practical for wind applications. The sliding wear performance of the borided surface is shown to be improved by an order of magnitude compared to that of standard carburized gear steels.

The lubricant-derived DLC technology introduces a paradigm shift in lubricant/material technologies. The concept is to design coatings that catalyze a reaction with base lubricants to form a protective boundary film. The advantage of this technique is that it can generate boundary films from oils that do not contain organometallic additives. This simplifies the lubricant formulation and removes additives, which in some cases can cause early failure in some wind applications. The results presented showed scuffing performance of these designer coatings that exceeded the limits of the test rig, Surface analysis showed evidence of diamond-like, sp3 bonding in the boundary film.

Finally, the nano-particle-based lubricant additives have been under development for several years to enhance performance compared to traditional additive packages. Nano-particle additives, mostly based on boron or carbon, are engineered to interact with the contacting surface to produce a low friction/protective boundary film. Results demonstrate the friction reduction qualities and surface analysis shows evidence of the tribofilm. Micro-pitting performance also was significantly enhanced with nano-boron additives compared to commercially-formulated oils. In the current test, micro-pitting was nearly eliminated.

The conclusion is that ultra-fast surface boriding can enhance surface hardness and reduce wear of certain components. More development is needed to optimize the processing for specific drive train components:

- Lubricant-derived DLC coating technology is an area of development that can reduce the need for traditional lubricant additives
- Nano-particle-based additives demonstrate certain advantages on the bench-top scale that need verification at the system level.

Novel Macromolecular Nano Lubricant Oils and Greases

Ajay P. Malshe, NanoMech Inc.

Successful investigations of advanced nano-lubricant additives that favorably impact robust boundary tribofilm formation to reduce wear and friction in wind turbine components, such as gearboxes, was presented. These additives are designed as surface-stabilized nanoscale, materials-based macromolecules that are “dropped-in” from off-the-shelf formulated oils and grease for the purpose of advancing effectiveness. They have been prepared for use in performance testing to closely simulate the conditions faced by oil lubricants and greases in wind turbines. Specimens of the most widely used materials in wind turbine gearboxes have been prepared for evaluation in several tribological tests to assess the performance of the developed nano-lubricants. These tests were used to demonstrate successful and consistent performance, meeting the demands for lubrication of wind turbine gearboxes.

Update on the Development of a Full Life Wind Turbine Gearbox Lubricating Fluid

Manfred Jungk, Dow Corning

The goal of this project is to prove and implement an alternative chemistry for the lubricating fluid used for wind turbine gearboxes. Due to the chemical robustness of the altered lubricating fluid, the expectation is that the need for condition monitoring and/or maintenance of the gearbox is reduced significantly and could potentially be eliminated. The fluid technology to be expanded into gearbox lubrication has been successfully used in "lube for life" specialty applications. In this study, bench testing like FZG gear and FE 8 bearing have been carried out to document the suitability of the fluid compared to existing gearbox oil specifications. The benefits, such as superior viscosity temperature profile with viscosity indices above 300, and material compatibility have been demonstrated. The target viscosity's superior viscosity temperature profile is lower than that currently used gearbox oils and results in friction reduction and reduced wear of the internal gears and components. Full-scale wind turbine gearbox trial results indicate improved power output efficiency. In addition to the increase of efficiency, the other potential impact is increased operating reliability through reduction in the downtime by eliminating planned and unplanned gear oil changes.

Modeling Tribological Contacts for Wind Turbine Gearbox Component Life Prediction

Nathan Bolander, Sentient Corporation

Modeling of lubrication and contacting surfaces can provide more accurate and flexible options for determining the life of wind turbine components. A few techniques that are being developed to improve the understanding of surface contact fatigue were presented. First, a brief introduction to EHL/mixed-EHL modeling was presented, including discussion of the governing equations and discretization techniques. The utility of a mixed-EHL approach, based on deterministic consideration of surface roughness profiles, was emphasized. In the next section, a microstructure-based approach for contact fatigue analysis was presented. The approach utilized detailed mixed-EHL traction profiles as inputs. Users can model the effect of a wide range of parameters that influence surface fatigue, such as surface roughness, material properties, and load variation. The analysis resulted in a fatigue life distribution. The final section showed a method by which a prognostic model for the remaining life of wind turbine components can be assembled from a damage progression model, a source of diagnostic information, and an uncertainty management model to update the architecture. A prognostic model for bearing spall propagation was presented as an example application.

Inputs for traction modeling (EHL/mixed-EHL) assume:

- Real surfaces are rough
- Reynolds equation governing lubrication flow in the contact zone
- Model outputs are a time history of surface shear stress, due to lubricant flow and asperity interaction.

In terms of fatigue damage initiation, there are several points to remember:

- Fatigue cracks initiate in the microstructure
- To understand fatigue, an understanding of microstructure level stresses is needed
- Fatigue models must consider:
    - Microstructure geometry/composition
    - Residual stresses due to manufacturing
    - Surface tractions
    - Load history/non-linear damage accumulation.

When developing a prognostic system, it is necessary to include three primary components:

- A damage progression model
- A source of diagnostic information
- An architecture to update predictions and manage the model uncertainties.

Approaching Surface Fatigue Life by Integrated Contact and Lubrication Mechanics

Jane Wang, Northwestern University

Surface damage due to contact fatigue is a major threat to wind turbine transmission gears and bearings. Fatigue life prediction is based on interfacial mechanics, and therefore, is vital to design, operation monitoring, and performance/reliability improvements. Over the years, a comprehensive fatigue life prediction approach has been developed for components under cyclic motion, based on advanced contact mechanics and mixed elastohydrodynamic lubrication (EHL) models. The comprehensive approach is capable of simulating the entire transition from full-film and mixed EHL down to boundary lubrication, or even dry contact, of real machined rough surfaces under severe operating conditions. The presentation introduced the models and predicted gear pitting life results with comparisons to test data. In addition, issues like material inclusions, defects, reinforcements, and surface treatments, such as coatings and case hardening, were discussed.

Panel Discussion

Field Observations of Tribological Damage in Wind Turbines

Art Miller, enXco

Four examples of wind turbine gearbox faults, discovered during end of warranty (EOW) inspections, were presented. The first case demonstrated micropitting and fretting on the planet gear, micropitting and scuffing on the ring gear, intermediate gear and pinion, and high speed gear and pinion. The second case was a gearbox with a failed non-drive end tapered roller bearing on one of the three planet gears. The gearbox in the third case demonstrated a pitted intermediate pinion and correlating oil debris sensor data. The gearbox in the fourth case showed pitting and smearing on the high speed shaft bearing. Conclusions were that oil cleanliness and quality does appear to be a contributing factor and flushing out the gearboxes and replacing clean gear oil appears to retard the progression of wear. Some of the gear oils seem to be better at controlling the foam. Testing brands that are outside of the OEM's list of recommendations are worth looking into. Viscosity is the most important property when choosing a lubricant and working with higher viscosities and oil with a higher index (VI) has had positive results

A Look at Wind Turbine Gearbox Oil over Time

Bill Herguth, Herguth Laboratories, Inc.

Examinations of seven different oils, from May 2004 to October 2011, totaling 3500 samples with run times from 1 to 72,649 hours used in a variety of gearbox makes, models and locations, were presented. The results show that gearbox oils react in service in different ways and that trending the data helps in determining the end of life. There is enough data available to plan future lubricant change schedules. These should be based on new algorithms using oil type, in-service time, gearbox make and model and operating parameters. Additive concentration and type do not necessarily indicate the relative wear protection or useful life

Damage as Seen from a Wind Turbine Gearbox Manufacturer's Angle

Shawn Doner, Winergy

The wind turbine industry has cost issues related to gearbox reliability. Solutions to the reliability problems are paramount. The presentation began with an example of shallow spalling on the intermediate pinion that was widespread in a particular gearbox. It was determined that the problem was a lubricant issue due to high water content in the oil. The particular oil was sensitive to moisture, which lowered its load carrying capacity. Water in oil is a continuing concern in the wind industry. Field data is extremely important to gearbox manufacturers to implement knowledge in future designs for continuous improvement. Winergy views the lubricant as a machinery element, an integral part of the overall design. Winergy has completed FZG tests to evaluate the effectiveness of oils with 500 parts per million (ppm) water, and also without water in the oil. One oil failed at load stage 5, others completed load stage 10.

Pitch and Yaw Bearing Damage

Les Miller, Kaydon

Dimensional challenges regarding the size and weight of pitch and yaw bearings in modern wind turbines were discussed, along with the magnitude of required preload to support the blade. Key issues with design and maintenance of pitch and yaw bearings were summarized. Smooth rotation is a continuing challenge in the presence of heavy preload and hub flexibility. Seal integrity and durability also are a continuing challenge and are important to increase resistance to false brinelling and fretting wear. There is currently no accurate means to predict friction torque under load. Life calculations such as L_{10} life are no longer required for certification, because the current designs are not failing due to fatigue. An example of a hub and bearing finite element analysis was presented, focusing on a large amount of deflection under a high preload. Examples of damaged pitch and yaw bearings also were shown. Adaptive pitch control was discussed with the possibility that it may resolve fretting, but it can result in fatigue issues.

Summary and Conclusions

Tribology is an interdisciplinary topic, involving interactions of fluid and surface chemistry to the physics of solid contact. In the wind energy community, tribological failures also are an inter-industry challenge because they include the bearing and gear OEM, lubricant formulator, turbine manufacturer, and operator. Therefore, a coordinated R&D effort is important to successfully identify, solve, and implement mitigation methods. DOE has the ability to approach the issues across industry boundaries and to provide information sharing that benefits the industry as a whole. DOE is also able to leverage the national laboratories and their unique capabilities and facilities, with the experience and application guidance of its industrial partners.

Research

There are several national laboratory research projects, in the past and ongoing, to address wind turbine tribological-related issues from varied approaches. Currently, the NREL Gearbox Reliability Collaborative (GRC) is working to understand the drive train system and account for load conditions that result in overstressed contacting elements. The GRC is utilizing advanced computer simulations, dynamometer testing, and field trials. In addition, its database effort is collecting information on field failures of gearboxes to elucidate the types of failures experienced by a range of turbine models at various locations. Argonne National Laboratory is engaged in the development of advanced surface treatments and lubricant additives that can benefit the wind industry, and has unique bench-top testing capabilities and lab-based coating and lubricant fabrication equipment. Oak Ridge National Laboratory also has unique tribology and metallurgy capabilities, and has been engaged in the forensic analysis of damaged wind turbine bearings using advanced microscopy techniques.

Seminar Summary

The reliability of a wind turbine is highly dependent on tribological issues associated with blade pitch systems, main shaft bearings, yaw systems, gearboxes, and generators. Many of the failure modes that occur in these systems such as Hertzian fatigue, adhesion, abrasion, corrosion, fretting corrosion, polishing, electric discharge, and scuffing are influenced by tribology. Lubricant base oil, additives, and cleanliness must be correctly specified for each of these systems to achieve their design life. Currently, bearings in blade pitch systems, main shafts, yaw systems, gearboxes, and generators suffer early failures despite well maintained systems, proper lubricant selection, and clean oil. Furthermore, micropitting continues to attack gear teeth and bearing components. False brinelling and fretting corrosion are the primary failure modes for blade pitch and yaw bearings, and electric discharge is often the root cause of failures of generator bearings. Lubricant contamination by solid particles is a principle mechanism that causes debris dents on bearing components. These eventually lead to micropitting and macropitting. A recent critical bearing problem manifesting as axial cracks is occurring primarily in the inner rings of bearings, though also sometimes in outer rings. Currently, there are several controversial hypotheses for the root cause of this failure mode, but none of the hypotheses have been widely accepted across the entire tribology community.

Tribology and Lubrication Fundamentals

As previously stated, tribology is an interdisciplinary topic, and a review of these fundamentals is essential for an informative understanding on how the entire wind turbine system operates. For wind turbine applications, there are several factors that cause extreme tribological conditions, which lead to early failure and system down time. These conditions are listed in the following section. The fundamental tribological topics that are most relevant to wind applications, which were covered in this seminar, included elastohydrodynamic lubrication behavior and surface interaction, and lubricant fundamentals: formulation, synthetics, and greases.

Elastohydrodynamic lubrication (EHL) is one characteristic to counter formal contact, like rolling element bearings and gear tooth contact. In the EHL lubrication regime, the surfaces are separated by a thin lubricant film, which is influenced by the lubricant, surfaces and contacting conditions. If the surface roughness is on the same order or greater than the generated film thickness, contact occurs. This is characterized as mixed lubrication, increasing the risk of surface damage, such as asperity scuffing and micropitting. It can be effectively controlled by reducing the surface roughness through super finishing techniques. An important parameter for designing components that operate in the EHL regime is the traction or friction at the contact. A protocol for extracting this parameter was proposed.

Lubricants used in wind turbine applications are subjected to extreme conditions and are expected to maintain their performance throughout operation, and therefore, they are required to meet higher standards than similar lubricants for other industries. Synthetic lubricants typically offer the better cost benefit throughout the life cycle. Development of new lubricants typically involves a systemic approach of blending different concentrations of certain additives to balance the various performance characteristics: scuffing, micropitting, wear, oxidation stability, compatibility with elastomers and paints, foaming, and other techniques. In addition to gear oils, greases are used in many bearing components: generator, main shaft, pitch, and yaw; each with their own design requirements.

Factors Influencing Surface Failures

It is clear that wind turbines offer unique environments for mechanical systems due to factors such as:

- Vibration loading
- Rapid acceleration
- Frequent stops and starts
- Periods of standstill during parking
- Misalignment of gears and bearings, due to elastic deformations
- Exposure to contamination by water and dust
- Exposure to wide temperature variations
- Difficult access for maintenance.

Because of this unique operational environment, it is important to maintain the quality of the lubricant by:

- Monitoring the life cycle of the oil- like the onset of oxidation and organic species in the oil
- Monitoring viscometrics, additive chemistry, contamination species (wear) and degradation
- Filtering the oil. There is no filter too small that would filter out additives; however, lubricant additives may absorb on the filter medium.

Critical Surface Damage/Failure Modes

Several surface damage mechanisms were identified as significant for wind turbines throughout the seminar, including false brinelling and fretting corrosion, mainly in blade pitch and nacelle yaw components, micropitting, abrasive wear, scuffing (also called smearing in bearing literature), axial cracking of bearing rings associated with irregular microstructural changes (also known as IrWEAs), Hertzian fatigue, electrical discharge damage, mainly in generator bearings, and surface etching/corrosion. Without a comprehensive collection of failure data and analysis, it is difficult to quantify the severity and frequency of each type of failure; however, anecdotal accounts during the seminar highlighted certain damage modes.

Some of the damage modes are summarized below:

- False brinelling and fretting corrosion, as it was pointed out by Doll and others, is a common issue for blade pitch and yaw bearing and gear components, which only experience a small range of motion or structural vibration. This condition causes lubricant to be squeezed out of the contact area and removes protective oxide layers. This results in an accelerated wear mode that forms indentations in the raceway, impeding the smooth operation of the positioning system. To alleviate these issues, certain control and design parameters to avoid critical dithering angles are recommended, in addition to the use of coatings and lubricating greases with proper antiwear additives.
- Micropitting is a wear mode that affects both gears and bearings, and is typically associated with tangential shear stress caused by rolling-sliding contact. In bearings, this is typically caused by sliding or skidding during unsteady operation. Micropitting is commonly a precursor to larger surface failures such as Hertzian fatigue (also caused by overstressed contact, material inclusions, and other factors). Micropitting has been and continues to be an issue that the wind industry has dealt with over the years and was the topic of a similar seminar titled “Wind Turbine Micropitting Workshop.” The outcome of this report included recommendations for run-in procedures, discussion of root causes, and recommendations for testing and future research. In general, the major factors influencing micropitting include inadequate EHL film thickness, surface roughness, unsteady operating conditions, and antiwear lubricant additives. The fundamental mechanisms that cause micropitting are still a matter of discussion and more work is needed in this area to fully characterize this damage mode. The standardized testing method for micropitting performance is reported to be inaccurate and misleading to

designers, which has perpetuated this problem. There is a critical need to reevaluate the standardized test method and consider different approaches.

- Scuffing is a surface damage mode of sliding contact typically characterized by the severe adhesion and rapid plastic deformation. It is caused by local frictional heating at the surface where lubrication film thickness is inadequate. This is generally understood as a lubrication short-fall, caused by inadequate design, lubricant supply, and additive formulation. Mitigation methods are fairly well established in the form of EP lubricant additives or surface coatings. However, this type of damage is commonly observed in field failures and a better understanding of the occurrences is needed. This would involve an analysis of specific failures including operating conditions leading to failure and bearing/gear location and design.
- Electric discharge damage can occur when faulty insulation, induction effects, or improper grounding allows the electric current to pass through the bearing, thereby damaging the bearing surfaces. Electric discharge damage is caused by electric arc discharge across the oil film, between the rollers and raceways. Electric current might originate from electric motors, electric clutches, instrumentation, or it might be due to the accumulation of static charge and subsequent discharge. Damage might occur during electric welding on, or near, the gearbox, if the path to ground is not properly made around the bearings rather than through them. Wind turbine bearings might be damaged by lightning strikes. When an electrical arc occurs, it produces temperatures high enough to melt bearing surfaces. Microscopically, the damage appears as small, hemispherical craters. Edges of the craters are smooth and they might be surrounded by burned or fused metal in the form of rounded particles that were once molten. A metallurgical section, taken transversely through the craters and acid etched area, might reveal austenitized and rehardened areas in white, bordered by tempered areas in black. Sometimes microcracks are found near the craters. Overall, damage to bearings is proportional to the number and size of the arcing points. Depending on its extent, electric discharge damage might be destructive to bearings. Associated microcracking might lead to subsequent Hertzian fatigue or bending fatigue. If arc burns are found on bearings, all associated gears should be examined for similar damage. Electric discharge damage can be prevented by providing adequate electrical insulation or grounding and by ensuring that proper welding procedures are enforced.
    - Arcing - Electric discharge damage might consist of randomly spaced discharge craters; this damage is designated as arcing
    - Fluting - Electric discharge damage is often periodically spaced around the raceway giving it a "fluted" or "washboard" appearance. The flutes are depressions in the raceway transverse in the rolling direction and are separated from each other by lands of undamaged surface. Fluting generally leads to high vibration and noisy operation.
- Microstructural alteration (i.e., white etching area cracks) is a class of damage mode that can lead to axial cracking and macropitting at 1% to 20% of the L_{10} bearing design life (Gegner). As discussed previously in this report, this is one of the more critical, and least understood, failure modes experienced in wind turbines. While not unique to the wind industry, it is found to be much more prevalent than in other applications. As reported,

there are several theories about the cause of WEA cracks including hydrogen induced embrittlement from lubricant decomposition (Uyama); mechanically induced, from high stress and slip conditions (Evans); mechanical impact loading (Luyckx); or multiple influencing factors, without one root cause (Holweger). No one root cause, or combination of multiple root causes, has been fully established and more fundamental research effort is needed to address this critical issue. Furthermore, the influence of materials, lubricants, and loading conditions on IrWEA cracking occurrence needs to be established through carefully designed test procedures, which are not yet established. Mitigation methods need to then be validated and optimized. Table 2 compares the current hypotheses for axial cracks.

Table 2. Comparison of Hypotheses for Axial Cracks

Hypothesis	Crack origin	Failure mechanism	Root cause
NSK	Subsurface	Hydrogen enhanced localized plasticity (HELP)	Hydrogen embrittlement, due to lubricant decomposition
SKF	Surface	Brittle fracture followed by crack propagation due to corrosion fatigue cracking	Tensile stress, due to high surface traction
Hansen	Subsurface	Adiabatic shear bands	Elastic stress waves, due to impact on surface asperities
Schaeffler	Subsurface	Severe plastic deformation	Complex interaction between lubricant, surfaces, materials, and loads

To facilitate communication between failure investigators, the nomenclature of failure modes for gears and bearings should be harmonized. Table Error**! No text of specified style in document.** recommends failure mode nomenclature and includes commonly used, but non-preferred names.

Table 3. Recommended Failure Mode Nomenclature

Failure mode	Preferred name	Non-preferred names
Hertzian fatigue	Macropitting	Spalling, pitting
Hertzian fatigue	Micropitting	Peeling, superficial spalling
Scuffing	Scuffing	Smearing, scoring

Field Failure Tracking and Analysis

Without statistical tracking of the field failures and root cause analysis, it is difficult to have a comprehensive account of the critical failure modes and to quantify the impact of each failure type. The NREL Gearbox Reliability Collaborative database effort is focused on facilitating this activity by working with wind farm owners and operators to develop the strategy to collect and analyze failure data. This helps to focus research efforts, and also aids in the development of appropriate mitigation methods through detailed forensic analysis. The database currently has collected 36 failure instances to date and expected to expand significantly in the near future.

Opportunities for Learning and Path Forward

The following list of discussion points was made by presenters and seminar participants on the topic of lessons learned within this and other industries.

- Comparisons with the aerospace industry should be considered for approaches to overcoming tribological challenges.
- Rolling element bearings in the aerospace industry generally have much longer, lives, ten years or more, even though they are subjected to highly loaded conditions.
- WEA issues are of interest to the aerospace industry as bearings reach their design life.
- The aerospace industry has experience of solving one issue at the expense of another issue. Therefore, system testing is critical for wind turbine design.
- Moving technology through technology readiness levels (TRL) 5, 6 ,7, and 8 (prototyping, system testing, demonstration, and application) and then to market requires costly testing. Coordinated and focused R&D programs are critical, including collaboration where applicable.
- TRL 4 (component level lab testing) is the critical point when technologies merge together. In tribology, synergies between lubricants, materials, and system design are identified at this point.
- Some tests are not appropriate and may mislead the design and, thus, the choice of solutions. Some testing methodologies are in house and not publicly available. Improvement of test methods is recommended versus the addition of more tests. Identification of tests that appropriately replicate the conditions leading to a certain failure or performance metric are necessary where there is no well excepted standardized test method.
- With many MW size turbines reaching the end of warranty, operators now can test new oils and may be willing to share data to spur development.
- Verification of new lubricant and surface/material technologies is critical to advancement. Typical verification period out-of-laboratory is 2 years of field testing for lubricants by some OEMs.
- Scaling issues seem to be a root cause for many tribology related failures, along with rapid market development, which requires time to tease-out issues experienced in the field.
- Material, coating, and lubricant development will take an industry-wide collaboration.

Recommendations for Future R&D Activity

The final session of the seminar was dedicated to a discussion of R&D needs moving forward to address the critical tribological issues discussed throughout the seminar. Given the breadth and depth of the seminar participants, the input to this process was informative.

It is noted that the surface failures observed in wind turbines are not fundamentally different from failures observed in other applications; however, the severity, frequency, and uncertainty of root causes for many of these failures has led to a reexamination of fundamental understandings and testing methodologies. Throughout this seminar, specific tribological topics clearly highlight needed R&D efforts. General R&D approaches are listed in 4 and recommendations for addressing specific issues are in 5.

Table 4. Research Needs in Wind Turbine Tribology: General R&D Approach

Item	Subject	Description
A	Failure analysis of components	Collection of in-field failed components and conducting detailed analysis and characterization using advanced methods to determine the morphology of failures across a large population and across component types and varied operating conditions. Collection of operational load and environmental spectra and the examination of components before failure also provides a better understanding of the factors that cause certain failures and how to control them.
B	Quantification and classification of failures	Utilize field failure data to quantify the criticality of different failure modes and focus efforts. Also requires an effort to standardize the description and classification of failure modes, especially for WEA and micropitting.
C	Test methodology development to mimic field failures	In conjunction with item 'A,' develop bench-top test methodology that accurately recreates the surface damage observed in the field. Reexamine standardized tests and make recommendations to improve test standards. Publicize test methodology.
D	Identify drivers: operational, environmental, materials, and others	Isolate the individual drivers for each failure mode and test the acceptable limits for each driver; this can include water composition of lubricant, particle size of contamination, operation limits at the contact, and more
E	Bench-top testing of mitigation methods	Utilizing test methodologies established in item 'C;' conduct screening of specific mitigation methods; such as coatings, lubricants, materials, and others.
F	System validation	Further validate mitigation methods proven in bench-top testing at the system level, in dynamometer and infield environments.
G	Modeling and analysis	Develop models used for simulating contact conditions and failure analysis. Validate with experimental data and utilization for understanding the fundamental tribological interactions.

Table 5. Research Needs in Wind Turbine Tribology: Specific Issues

Recommendations for Addressing Specific Issues		
H	Analysis of lubricant additive interaction	Typical additives may have an adverse effect in certain conditions. For example, antiwear additives might inhibit run-in and promote micropitting; decomposition of additives might cause adverse effects on the bearing and gear material.
I	Establish a strategic approach to investigating WEA	A standardized approach to examining WEA formation is needed to understand root causes and test different theories. Some key items include the role of material microstructure, i.e. level of retained austenite in carburized layer; identification of mechanical drivers; development of test methodology to mimic mechanical conditions, i.e., impact loading; understanding the connections between mechanical drivers and material science; computer modeling to isolate certain mechanisms; role of lubricant chemistry
J	Lubricant aging studies	Changes in lubricity, antiwear characteristics, and corrosiveness of lubricants subjected to aging in the field need to be better characterized. At what point these changes can lead to surface damage needs to be better established.
K	Black oxide influence	Black oxide is a common treatment method; however, it is uncertain how it is influencing certain failure modes (adversely or beneficially). Comprehensive testing is needed to examine its role and recommendations for future application.
L	Lubricant filtering study	Filtering lubricants to remove particle and water contamination is important to keep oil clean and functioning properly. There is some question as to whether lubricant additives react with the filtering medium removing it from the oil. Testing and consensus is needed.
M	Surface finish	It is generally accepted that smoother surfaces are better for avoiding micropitting, scuffing, and wear. Super finishing techniques are available; however, there is some debate on what level of smoothness is required and if there is a level of "too smooth."
N	Surface engineering	Coating and other surface engineering is an ongoing area of research in many industries. In wind, where cost is critical, an evaluation of coating performance and benefit is needed. This may lead to development of new, better performing, and cost effective coatings that meet wind requirements.
O	Advanced base lubricants	Synthetic lubricants are becoming common in the wind industry. New classes of synthetic lubricants need to be evaluated with respect to cost and safety.
P	Advanced lubricant additives	Traditional organo-metallic EP additives have certain performance limitations and questionable interaction with certain materials, in addition to environmental concerns. New additives,need to be evaluated and optimized for wind application.

Bibliography

Atsushi, U., Tsutomu, S., and Kouichi, I., US patent 2007/0044543 A1 (2007).

Bhadeshia, H. K. D. H., "Steels for Bearings," *Progress in Materials Science*, Vol. 57 (2012), pp. 268-435. doi:10.1016/j.pmatsci.2011.06.002

Balcombe, R., Fowell, M.T., Olver, A.V., et al., A Coupled Approach for Rolling Contact Fatigue Cracks in the Hydrodynamic Lubrication Regime: The Importance of Fluid/Solid Interactions, *Wear*, 271 (2011) 720-733.

Bartz, W. J., Tribologische Aspekte bei Zahnradgetrieben - Speziell für Fahrzeuge,Prof. T+S Tribologie und Schmierungstechnik, Denkendorf 5, *Internationales CTI Symposium*.

Baumann, G., Fecht, H. J., and Liebelt, S., Formation of white-etching layers on rail treads, *Wear,* 191 (1996) 133-140.

Becker, P. C., Microstructural changes around non-metallic inclusions caused by rolling-contact fatigue of ball-bearing steels. *Metals Technology,* June (1981) 234 – 243.

Biboulet, Nans, Influence of Indentations on Rolling Bearing Life. *Doctoral Thesis in Mechanical Engineering*, I.N.S.A. de Lyon (2008).

Blau, P. J., Walker, L. R., Xu, H., Parten, R., Qu, J., and Geer, T., *Wear Analysis of Wind Turbine Gearbox Bearings*. Oak Ridge: Oak Ridge National Laboratory, 2010.

Brückner, M., Gegner, J., Grabulov, A., Nierlich, W., and Slycke, J., Butterfly Formation Mechanisms in Rolling Contact Fatigue. *Proceedings of the 5th International Conference on Very High Cycle Fatigue, Berger, C. and Christ, H.-J. (Eds.),* German Association for Materials Research and Testing (DVM), Berlin, (2011) 101 – 106.

Chen, W. W. and Wang, Q., A Numerical Model for the Point Contact of Dissimilar Materials Considering Tangential Tractions, *Mechanics of Materials*, Vol. 40 (2008), pp. 936 - 948.

Chen, W. W. and Wang. Q., "Thermomechanical Analysis of Elasto-Plastic Bodies in a Sliding Spherical Contact and the Effects of Sliding Speed, Heat Partition, and Thermal Softening," *Journal of Tribology*, Vol. 130 (2008), pp. 041402-1-10.

Chen, W. W., Wang, Q., Wang, F., Keer, L. M., and Cao, J., "Three-Dimensional Repeated Elasto-Plastic Point Contact, Rolling and Siding," *Journal of Applied Mechanics*, Vol. 75 (2008), pp. 021021-1-12.

Chen, W., W., Kim, W., and Wang, Q., Transient Thermomechanical Analysis of Sliding Electrical Contact of Elasto-Plastic Bodies, Thermal Softening and Melting Inception, *Journal of Tribology*, Vol. 131 (2009), pp. 021406-1-10.

Chen, W., W., Zhou, K., Keer, L. M., and Wang, Q., 2010, "Modeling Elasto-plastic Indentation on Layered Materials Using the Equivalent Inclusion Method," *International Journal of Solids and Structures*, doi:10.1016/j.ijsolstr.2010.06.011, Vol. 47, 2841–2854.

Chen, W., W. and Wang, Q., A Numerical Static Friction Model for Spherical Contacts of Rough Surfaces, Influence of Load, Material, and Roughness, *Journal of Tribology*, Vol. 131 (2009), 021402-1-8.

Chikara, O., and Tomoaki G., US patent 2001/0179161 A1 (2001).

Clos, R., Schreppel, U. and Veit, P., Chip formation and strain localization in 100Cr6, *1st Colloquium Processscaling*, Bremen, 28./29.10. (2003).

Errichello, R. Another Perspective: False Brinelling and Fretting Corrosion, *Tribology & Lubrication Technology*, 60 (2004) 34-36.

Errichello, R., and Muller, J., Oil Cleanliness in Wind Turbine Gearboxes, *Machinery Lubrication*, 2, 4 (2002) 34-40.

Errichello, R., Friction, Lubrication, and Wear of Gears, *ASM Handbook*, 18 (1992) 535-545.

Errichello, R., Gear Lubricant Selection and Application, *Tribology Data Handbook*, Chap. 67, CRC Press (1997).

Errichello, R., GEARTECH Report No. 2443, Failure Analysis of NREL Field Test Gearbox No. 1, Prepared for NREL under Subcontract No. LEE-7-77535-01, Jan. 21 (2011) 1-60.

Errichello, R., IrWEA and Axial Cracks in WT Bearings, *Memo*, Nov. 9 (2011).

Errichello, R., Milburn, A., and Godfrey, D., Polishing Wear, *AGMA 90FTM5* (1990).

Errichello, R., Rougher Surfaces Give Longer Gear Life?, *Gear Technology*, 23, 3 (2006) 30.

Errichello, R., Selecting and Applying Lubricants to Avoid Micropitting of Gear Teeth, *Machinery Lubrication*, 2, 6 (2002) 30-36.

Errichello, R., Selecting Oils with High Pressure-Viscosity Coefficient, *Machinery Lubrication*, 4, 2 (2004) 48-52.

Errichello, R., Spalled Bearings, *Practicing Oil Analysis*, 7, 5 (2005) 68-70.

Errichello, R.L., Morphology of Micropitting, *AGMA 11FTM17* (2011).

Errichello, R.L., Point-Surface-Origin, PSO, Macropitting Caused by Geometric Stress Concentration, GSC, *AGMA 10FTM11* (2010).

Evans, M.H., “White Structure Flaking (WSF) in Wind Turbine Gearbox Bearings: Effects of ‘Butterflies’ and White Etching Cracks,” *Materials Science and Technology*, Vol. 28, No. 1, 2012, pp. 3 – 22.

Faulstich, S., Hahn, B., Jung, H., and Rafik, K., 2009 Suitable Failure Statistics as a Key for Improving Availability, Paper Number PO.303, *Proceedings of the EWEC*, Marseille, France (2009).

Fujita, Uchida, and Tanaka, Long-Life Materials Countering White Structure Flaking, *NSK Technical Journal Motion & Control,* 19 (2006) 20-26.

Fukui, S., “The Effect of Tempering on the Delayed Fracture Characteristics of Low-Alloy Steels,” *Tetsu-to-Hagane*, Vol.55, No. 2 (1969), pp. 151-161.

Gegner, J. and Nierlich, W.: Mechanical and Tribochemical Mechanisms of Mixed Friction Induced Surface Failures of Rolling Bearings and Modeling of Competing Shear and Tensile Stress Controlled Damage Initiation. *Tribologie und Schmierungstechnik*, 58, 1, (2011)10–21.

Gegner, J. and Nierlich, W.: Operational Residual Stress Formation in Vibration-Loaded Rolling Contact. *Advances in X-ray Analysis*, 52 (2008) 722-731.

Gegner, J. and Nierlich, W.: Hydrogen Accelerated Classical Rolling Contact Fatigue and Evaluation of the Residual Stress Response. *Materials Science Forum*, 681, (2011) 249–254.

Gegner, J. and Nierlich, W.: Sequence of Microstructural Changes during Rolling Contact Fatigue and the Influence of Hydrogen. *Proceedings of the 5th International Conference on Very High Cycle Fatigue, Berger, C. and Christ, H.-J. (Eds.), German Association for Materials Research and Testing (DVM)*, Berlin, (2011) 557–562.

Gegner, J.: Post-Machining Thermal Treatment (PMTT) of Hardened Rolling Bearing Steel. *Proceedings of the 4th International Conference on Mathematical Modeling and Computer Simulation of Material Technologies*, 1, College of Judea and Samaria, Ariel, Israel, Chap. 2, (2006) 66–75, http://www.ariel.ac.il/sites/conf/mmt/MMT-2006/Service_files/papers/Session_2/2-066_po.pdf.

Gegner, J., Evidence and analysis of thermal static strain aging in the deformed surface zone of finish-machined hardened steel, *Powder Diffraction Suppl.*, 24, S1, June (2009) 45-50.

Gegner, J., Nierlich, W., and Brückner, M., Possibilities and extension of XRD material response analysis in failure research for the advanced evaluation of the damage level of Hertzian loaded components, Mat.-wiss. u. Werkstofftech 38, 8 (2007) 613-623.

Gegner, J., Post-Machining Thermal Treatment (PMTT) of Hardened Rolling Bearing Steel, *MMT,* http://www.ariel.ac.il/management/research/pf/zinigrad/ mmt/MMT-2006/Service_files/papers/Session_2/2-066_po.pdf (04/2011) (2006) 2-66 - 2-75.

Gegner, J., Schlier, L., and Nierlich, W.: Evidence and Analysis of Thermal Static Strain Aging in the Deformed Surface Zone of Finish-Machined Hardened Steel. *Powder Diffraction*, 24, 2-supplement, (2009) 45–50.

Gegner, J.: Tribological Aspects of Rolling Bearing Failures. In: *Tribology – Lubricants and Lubrication, Kuo, C.-H. (Ed.), InTech, Rijeka, Croatia*, Chap. 2, (2011) 33–94, http://www.intechopen.com/articles/show/title/tribological-aspects-of-rolling-bearing-failures.

Grabulov, A., and Zandbergen, H.W., TEM and Dual Beam (SEM/FIB) Investigations of Subsurface Cracks and White Etching Area (WEA) Formed in a Deep Groove Ball Bearing Caused by Rolling Contact Fatigue (RCF), *Proceedings of VHCF-4 Conference* (2007).

Grabulov, A., Petrov, R., & Zandbergen, H.W., EBSD Investigation of the Crack Initiation and TEM/FIB Analyses of the Microstructural Changes Around the Cracks Formed Under Rolling Contact Fatigue, *Intl. J. Fatigue*, 32 (2010) 576-583.

Grabulov, A., Ziese, U., and Zandbergen, H.W., TEM/SEM investigation of microstructural changes within the white etching area under rolling contact fatigue and 3-D crack reconstruction by focused ion beam, *Scripta Materialia,* 57 (2007) 635-638.

Greco, A., Martini, A., Liu, Y., Lin, C., and Wang, Q., “Rolling Contact Fatigue Performance of Vibro-Mechanical Textured Surfaces”, *Tribology Transactions*, Vol. 53 (2010), pp. 610-620.

Greco, A., K. Mistry, V. Sista, O. Eryilmaz, and A. Erdemir, "Friction and wear behaviour of boron based surface treatment and nano-particle lubricant additives for wind turbine gearbox applications," *Wear*, 2011: 1754-1760.

Harada, H., et al., Microstructural Changes and Crack Initiation with White Etching Area Formation under Rolling/Sliding Contact in Bearing steel, *ISIJ International*, Vol. 45, No. 12 (2005) 1897-1902.

Harris, T. A., Rumbarger, J. H., and Butterfield, C. P., Wind Turbine Design Guide DG03: Yaw and Pitch Rolling Bearing Life, Technical *Report NREL/TP-500- 42362*, U.S. National Renewable Energy Laboratory, Golden, CO (2009).

Hiraoka, K., et al., “Study on Flaking Process in Bearings by White Etching Area Generation,” Bearing Steel Technology- Advances and State of the Art in Bearing Steel Quality Assurance,” *ASTM STP 1465*, ASTM (2007) 234-240.

Hiraoka, K., Nagoa, K., and Isomoto, T., Study on flaking process in bearings by white etching area generation, *J. ASTM Inti*., 3, 5, *ASTM International, West Conshohocken, PA, Paper ID JAI14059,* (2006).

Hooke, C. J., Dynamic Effects in EHL contacts, C.J. Hooke, Tribological Research and Design for Engineering Systems, *Proceedings of the 29th Leeds-Lyon Symposium on Tribology*, Elsevier B. V., (2003) 69-78.

Iso, K., Yokouchi, A., and Takemura, H., “Research Work for Clarifying the Mechanism of White Structure Flaking and Extending the Life of Bearings,” *NSK Technical Journal Motion & Control*, 19 (2006) 27-36.

Jin, X., Hasebe, N., Keer, L. M., and Wang, Q., A Comparative Study of Modeling the Magnetostatic Field in a Current-Carrying Plate Containing an Elliptic Hole, *IEEE Transactions on Magnetics*, Vol. 45 (2009) 1990-1998.

Kalogiannis, K., Mares, C., Glovnea, R. P., and Ioannides, S. Elastohydrodynamic film thickness response to harmonic vibrations, *International Multi-Conference on Engineering and Technological Innovation*, http://www.iiis.org/CDs2008/CD2008SCI/IMETI2008/PapersPdf/F687SR.pdf (04/2011). (2008).

Kaneta, M., Ozaki, S., Nishikawa, M., and Guo, F., Effects of impact loads on point contact elastohydrodynamic lubrication films, Sage Publications, *Proceedings of the Institution of Mechnical Engineers, Part J, Journal of Engineering Tribology*, 221, 3 (2007) 271-278.

Kawamura, H., and Egami, Study on Mechanism of Hydrogen Generation from Lubricants, *Tribology Transactions,* 49, 1 (2006) 53-60.

Kino, N., and Otani, K., The influence of hydrogen on rolling contact fatigue life and its improvement, *JSAE Review* 24 (2003) 289-294.

Kissling, U., Beermann, S., and Dinner, H., Un software per il calcolo a micropitting, *Organi di Transmissione - Settembre* (2010).

Kotzalas, M. N., and Doll, G. L., “Tribological Advancements for Reliable Wind Turbine Performance,” *Phil. Trans. R. Soc. A*, Vol. 368, No. 1929 (2010), pp. 4829-4850.

Krantz, T.L.; Alanou, M.P.; Evans, H.P.; Snidle, R.W., “Surface Fatigue Lives of Case-Carburized Gears with an Improved Surface Finish.” *J. Tribol.-T. ASME*; ISSN 0742-4787, Vol. 123, 2001; pp. 709-716.

Kreil, O., Einfluss der Oberflächenstruktur auf Druckverteilung und Schmierfilmdicke im EHD-Kontakt, *Oliver Kreil, TU München, Diss*, http://deposit.d-nb.de/cgi-bin/dokserv?idn=99328146x&dok_var=d1&dok_ext=pdf&filename=99328146x.pdf (04/2011) (2009).

Leonard, B.D., Sadeghi, F., Evans, R.D., Doll, G.L., and Shiller, P.J., Fretting of WC/aC:H and Cr2N Coatings under Grease-Lubricated and Unlubricated Conditions, *Tribology Transactions*, 53 (2010) 145-153.

Li, J. G., Umemoto, M., Todaka, Y., and Tsuchiya, K. A microstructural investigation of the surface of a drilled hole in carbon steels, *Acta Materialia*, (2006).

Link, H., et al., “Gearbox Reliability Collaborative Project Report: Findings from Phase 1 and Phase 2 Testing,” Technical Report, Golden: NREL, 2011.

Liu, Y., Wang, Q., Krupka, I., Hartl, M., and Bair, S., The Shear-Thinning Elastohydrodynamic Film Thickness of a Two-Component Mixture, *Journal of Tribology*, Vol. 130 (2008), pp. 021502-1-7.

Liu, Y., Zhu, D., and Wang, Q., Effect of Stiff Coatings on EHL Film Thickness in Point Contacts, *Journal of Tribology*, Vol. 130 (2008), pp. 031501-1-6.

Lu, Nanao, Kobayashi, Kubo, and Mori, Effect of Lubricant Additives on Tribochemical Decomposition of Hydrocarbon Oil on Nascent Steel Surfaces, *Journal of the Japan Petroleum Institute*, 53, 1 (2010) 55-60.

Lund, T. Sub-surface initiated Rolling Contact Fatigue - Influence of Steel Matrix, Non-metallic Inclusions and Operating Conditions, *8th International ASTM Symposium on Bearing Steel Technologies*, Vancouver, May, ASTM International, West Conshohocken (2009).

Luyckx, J., Broeders, W., and Geertsom, J., "Method for Increasing the Fatigue Strength of a Predominantly Steel Mechanical Part of a Wind Turbine and/or for Reducing the Tendency to Form what are Called 'White Etching Cracks' or 'Brittle Flakes' in such Steel Mechanical Parts", US Patent 2009/0288742 A1, 2009.

Martini, A., Zhu, D., and Wang, Q., Friction Reduction in Mixed Lubrication, *Tribology Letters*, Vol. 28 (2007), pp. 171-181.

McVittie, D., Wind Turbine Gearbox Reliability, The Nature of the Problem, *Wind Turbine Reliability Workshop*, (2006).

Meyer, L. W., and Krueger, L., Investigation of titanium alloys under biaxial impact loading, Approved for Public Release, (1997).

Michaelis, K., GEAR FAILURES Pitting, Gear Research Centre TU München, Course at the University of Ljubljana.

Miller, S. F., Blau, P. J., and Shich, A. J., Microstructural Alterations Associated with Friction Drilling of Steel, Aluminum, and Titanium, *Journal of Materials Engineering and Performance*, 14, 5 (2005) 647-653.

Mitamura, H., and Takaki, Microstructural Development in Bearing Steel during Rolling Contact Fatigue, *Material Science Forum*, 539-543 (2007) 4255-4260.

Molinari, A., Musquar, C., and Sutter, G., Adiabatic shear banding in high speed machining of Ti-6Al-4V: experiments and modeling, *International Journal of Plasticity*, 18 (2002) 443-459.

Morales-Espejel, G.E., Brizmer, V. and Stadler, K.: Understanding and Preventing Surface Distress. *evolution*, 18, 4, (2011) pp. 26-31.

Moreita de Freitas, D. F., Formation de phase blanche en fatigue de roulement, Scripta *METALLURGICA*, 17 (1983) pp. 683-686.

Murakami et al., *NSK Technical Journal*, No. 656 (1993).

Murakami et al., *Zairyo*, Vol. 54 (2005).

Nierlich, N., and Gegner, J., Material response models for sub-surface and surface rolling contact fatigue, *Proc MMT 1, Chap. 1,* http://www.ariel.ac.il/management/research/pf/zinigrad/mmt/MMT-2006/Service_files/papers/Session_1/1-182_ma.pdf (04/2011), (2006) 182-192.

Nierlich, W., and Gegner, J.: Einführung der Normalspannungshypothese für Mischreibung im Wälz-Gleitkontakt. Gleit- und Wälzlagerungen: Gestaltung, Berechnung, Einsatz, *VDI-Berichte 2147*, VDI Wissensforum, Düsseldorf, Germany, (2011) 277–290, in German.

Nierlich, W., and Gegner, J.: Material Response Models for Sub-Surface and Surface Rolling Contact Fatigue. *Proceedings of the 4th International Conference on Mathematical Modeling and Computer Simulation of Material Technologies*, 1, College of Judea and Samaria, Ariel, Israel, Chap. 1, (2006)182–192, http://www.ariel.ac.il/sites/conf/mmt/MMT-2006/Service_files/papers/Session_1/1-182_ma.pdf.

NSK info brochure, Long-Life Bearings for Engine Accessories.

Oila, A., Shaw, B. A., Aylott, C. J., and Bull, S. J., "Martensite Decay in Micropitted Gears", *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, Vol. 219 (2005), pp. 77-83.

Olver, A.V., Spikes, H.A., Bower, A.F., Johnson, K.L., "The Residual-Stress Distribution in a Plastically Deformed Model Asperity," *Wear*, Vol. 107 (1986) 151-174.

Österlund, R. and Vingsbo, O., "Phase Changes in Fatigued Ball Bearings", *Met Trans*, 11a (1980), pp. 701-707.

Pogdornik, B., Kalin, M., Vizintin, J., and Vodopivec, F., "Microstructural changes and contact temperatures during fretting in steel-steel contact," *Journal of Tribology*, Vol. 123, Oct. 2001, pp. 670-675.

Ramesh, A., Melkote, S. N., White Layer Formation in Machining of Hardened Steel: Experiments and Modeling, *High Speed Machining of Hard/Super Hard Materials*, November 7-11, Singapore, (2003).

Ren, N., Zhu, D., Chen, W. W., Liu, Y., and Wang, Q., A Three-Dimensional Deterministic Model for Rough Surface Line-Contact EHL, *Journal of Tribology*, Vol. 131 (2009) 011501-1-9.

Ren, N., Zhu, G., and Wang, Q., Three-Dimensional Plasto-Elastohydrodynamic Lubrication (PEHL) for Surfaces with Irregularities, *Journal of Tribology,* 133 (2011) 031502-1-10, DOI: 10.1115/1.4004100.

Rosinski, J., and Smurthwaite, D., Troubleshooting Wind Gearbox Problems, *Gear Solutions*, 8 (2010) 22-33.

Safa, M. M. A., and Gobar, R., Pressure Distribution Under a Ball Impacting a Thin Lubricant Layer, *Journal of Tribology*, 108 (1986) 372-376.

Sakai, T., Crack initiation mechanism of bearing steel in very high cycle fatigue, *Proceedings of European Conference of Fracture*, (2006).

Sauger, E., et al., Tribologically Transformed Structure in Fretting, *Wear*, 245 (2000) 39–52.

Schlicht, H., "Über die Enstehung von White Etching Areas (WEA) in Wälzelementen," HTM 28 (1973) 112-123.

Schlicht, H., Über die adiabatic shearbands und die Entstehung der Steilen Weißen Bänder in Wälzlagern, *Mat.-wiss. u. Werkstofftech*., 39, 3 (2008) 217 – 226.

Schlicht, H., und Broszeit, E., Die Werkstoffbeanspruchung im Wälzkontakt bei hoher Flächenpressung, ermittelt nach Hertz und nach der EHD-Strömungshypothese, *Mat.-wiss. u. Werkstofftech*., 38, 4 (2007) 255-262.

Sheng, S., Wind Turbine Micropitting Workshop: A Recap. Technical Report, Golden: NREL, 2010.

Shibata, M., Gotoh, M., Oguma, N., and Mikami, T., *Proc. of the Int. Tribology Conf., Yokohama*, (1995) 1351.

Siniawski, M., Harris, S., and Wang, Q., A Universal Wear Law for Abrasion, *Wear*, 262 (2007), pp. 883-888.

Skurka, J.C., "Elastohydrodynamic Lubrication of Roller Beaings," *Journal of Lubrication Technology*, Vol. 92, Ser. F, No. 2, April 1970, pp. 281-290.

Sperrfechter, T., Keramische Bauteile im elastohydrodynamische Kontakt, *Institut für Keramik im Maschinenbau, Universität Karlsruhe (TH)*, (1998) 1436-3488.

Srinidhi, S., Tiwari, M., Burra, R., Gowda, H., and Siemers, P., Bearing Wear due to Mechanical Stresses and Electrical Currents. *IJTC2009-15255 Proceedings of the ASME/STLE International Joint Tribology Congress*, Memphis, TN (2009).

Swahn, H. Becker, H., and Vingsbo, O., Martensite decay during rolling contact fatigue in ball bearings, *Metallurgical Trans. A*, 7A (1976) 1099-1110.

Tallian, T., "On Competing Failure Modes in Rolling Contact," *ASLE Transactions*, Vol. 10, No. 4, Oct. 1967, pp. 418-439.

Tallian, T., Failure Atlas for Hertz Contact Machine Elements, 2nd Edition, *ASME Press* (1999).

Tanaka, Pulley Support Bearings for Push-Belt CVTs, *NSK Technical Journal Motion & Control*, 19 (2006) 13-19.

Tanaka, S., Mitamura, N., and Murakami, Y., "Influence of Sliding and Chromium Content in the Steel on the White Structural Change under Rolling Contact," *Proc. Global Powertrain Congress*, Dearborn, MI, USA, September 2004, Global Powertrain Congress, Vol. 32, 6–13.

Uyama, Yamada, Hidaka, and Mitamura, The Effects of Hydrogen on Microstructural Change and Surface Originated Flaking in Rolling Contact Fatigue, *Tribology Online*, 6, 2 (2011) 123-132.

Vegter, R. H., and Slycke, J. T., The role of hydrogen on rolling contact fatigue response of rolling element bearings, *J. ASTM Intl*., Paper ID JAI102543 (2006).

Vincent, A., Fougères, R., Lormand, G., Dudragne, G., and Girodin, D., A Physically Based Endurance Limit Model for Through Hardened and Surface Hardened Bearing Steels, *Bearing Steel Technology, ASTM STP 1419*, J. M. Beswick, Ed, ASTM International, West Conshohocken, PA, (2002).

Vincent, A., Lormand, G., Lamagnère, P., Gosset, L., Girodin, D., Dudragne, G., and Fougères, R., From white etching areas formed around inclusions to crack nucleation in bearing steels under rolling contact fatigue, *Bearing Steels: Into the 21st Century, ASTM STP 1327*, J. J. C. Hoo and W. B. Green, Eds., ASTM International, West Conshohocken, PA, (1998) 109 – 123.

Voskamp, A. P., "Material Response to Rolling Contact Loading," *Journal of Tribology*, Vol. 107, Jul. 1985, pp. 359-366.

Wang, L., Microstructure and Residual Stress State in the Contact Zone of Rails and Wheels, *thesis*, Berlin, (2002).

Wang, Q., Zhu, D., Zhou, R., and Hashimoto, F., Investigating the Effect of Surface Finish and Texture on Mixed EHL of Rolling and Rolling-Sliding Contacts, *Tribology Transactions*, Vol. 51 (2008), pp. 748 – 761.

Wei, Q., Kecskes, L., Jiao, T., Hartwig, K. T., and Ramesh, K. T., Adiabatic shear banding in ultrafine-grained FE processed by severe plastic deformation, *E. Ma, Acta Materialia,* 52 (2004) 1859-1869.

Winkelmann, L., King, P. B., Bell, M., and Elsaeed, O., The Effect of Superfinishing on Gear Micropitting (Part I), *STLE Annual Meeting*, May (2008).

Winkelmann, L., King, P. B., Bell, M., and Elsaeed, O., The Effect of Superfinishing on Gear Micropitting (Part II), *AGMA 08FTM10* (2008).

Yang, Y., Xiong, J., and Yang, X., Microstructure evolution mechanism in adiabatic shear band in TA2, *Trans. Nonferrous Met. Soc. China*, 14, 4, (2004).

Zaretsky, E. V., ed., *Tribology for Aerospace Applications*, STLE SP-37, Society for Tribologists and Lubrication Engineers, Park Ridge, IL, 1997.

Zarestsky, E. V., ed., *STLE Life Factors for Rolling Element Bearings*, 2nd Ed., STLE SP-34, Society for Tribologists and Lubrication Engineers, Park Ridge, IL, 1999.

Zarestsky, E. V., "Rolling Bearing Life Prediction, Theory and Application," *Recent Developments in Wear Prevention, Friction and Lubrication*, G.K. Nikas, Ed., Research Signpost, Kerala, India, pp. 45-136, 2010.

Zhou, K., Keer, L. M., Wang, Q., and Hua, D., 2011, "Size Prediction of Particles Caused by Chipping Wear of Hard Coatings," *Wear*, Vol. 271, Issue: 7-8, 10.1016/j.wear.2011.05.020, pp. 1203-1206.

Zhou, K., Chen, W. W., Keer, L. M., Ai, X., Sawamiphakdi, K., Glaws, P., and Wang, Q., 2011, "Multiple 3D Inhomogeneous Inclusions in a Half Space under Contact Loading," *Mechanics of Materials*, Vol. 43, Issue 8, pp. 444-457.

Zhou, K., Keer, L. M., Wang, Q., Shah, B. M. and Su, F., 2011, "Modeling Damage to Real Surfaces in Contact within a Unified Framework," *Procedia Engineering*, Vol. 10, 2011, pp. 1573-1578.

Zhou, K., Chen, W, W, Keer, L. M., and Wang, Q., 2009, "A Fast Method for Solving Three-Dimensional Arbitrarily-Shaped Inclusions in a Half Space, *Computer Methods in Applied Mechanics and Engineering*, Vol. 198, pp 885-892.

Zhu, D., Ren, N., and Wang, Q., 2009, "Pitting Life Prediction Based on 3-D Line Contact Mixed EHL Analysis and Subsurface von Mises Stress Calculation," *Journal of Tribology*, Vol. 131 (2009), pp. 041501-1.

Zhu, D., Martini, A., Wang, W., Hu, Y., Lisowsky, B., and Wang, Q., 2007, "Simulation of Sliding Wear in Mixed Lubrication," *Journal of Tribology*, Vol. 129, pp. 544-552.

Zwirlein, O., and Schlicht, H., Rolling Contact Fatigue Mechanisms-Accelerated Testing Versus Field Performance, *ASTM 771, J.J.C. Hoo, Ed.*, ASTM (1982) 358-379.

Zwirlein, O., and Schlicht, H., Werkstoffanstrengung bein Wälzbeanspruchung - Einfluß von Reibung und Eigenspannungen, *Z. Werkstofftech*, (1980) 11, 1.

Appendix A. Moderator, Speaker, and Panelist Biographies

Nathan Bolander
Nathan Bolander is the Chief Scientist at Sentient Corporation in Idaho Falls, Idaho. He received a BSME degree from the University of Wyoming, and MSME and PhD degrees from Purdue University with an emphasis in Tribology. Nathan's expertise is in modeling of mixed-elastohydrodynamic lubrication and surface fatigue for bearings and gears.

H. R. (Henri) Braun
Henri Braun was born in 1957 in Cologne, Germany. He received his PhD in Inorganic Chemistry from the University of Cologne in 1988. In 1987, he began his career with Esso in its Research & Technical Support Laboratory in Hamburg. Since then, he has worked through various positions and jobs with Exxon, Exxon Chemical, and ExxonMobil in Germany, the UK, and Belgium. He is currently the Global Grease Technology Manager working from ExxonMobil Headquarters in Fairfax, VA, USA.

Shawn Doner
Shawn has been employed by Winergy Drive Systems Corporation since 2005 and has 25 years of mechanical systems experience. He has worked in operations and commercial roles, including gearbox remanufacturing, remanufacturing operations management, field service, and aftermarket sales. Shawn is currently the Technical Sales Support Manager at Winergy. He is currently pursuing his Bachelor's degree in Business Administration with a concentration in Green Sustainable Enterprises.

Gary Doll
Gary Doll is the Timken Professor of Surface Engineering and the Director of the Timken Engineered Surfaces Laboratories. His research interests include engineering surfaces to address friction, wear, and corrosion; the mechanical properties of superelastic materials and nanocomposites; and lubrication strategies for challenging environments. He received his PhD in Condensed Matter Physics from the University of Kentucky, where he studied the optical and structural properties of layered materials. As a postdoctoral fellow in Physics at the Massachusetts Institute of Technology, he conducted research on a wide range of materials including copper oxide superconductors, composites, carbon fibers, and polyimides. After MIT, he joined the General Motors Research Laboratories, where he began his research in thin film coatings, surface engineering, and tribology. Later, he became the Chief Technologist of Tribology at the Timken Company, where he was responsible for global research and development activities in bearing tribology, lubrication, surface engineering, and non-ferrous materials. Dr. Doll was elected as an ASM Fellow in 2009 for his contributions to the field of Surface Engineering. He currently serves as chair of the STLE/ASME Wind Energy Tribology Committee and is an assistant editor for Tribology Transactions. Throughout his career, Dr. Doll has published more than 150 articles and book chapters, edited four proceedings, and received more than 25 U.S. Patents.

Ali Erdemir
Ali Erdemir is a pioneering researcher, with international recognition and significant accomplishments, in the fields of materials science, surface engineering, and tribology. Dr.

Erdemir's discoveries of nearly frictionless carbon and superhard nanocomposite coatings, as well as boron-based solid lubricants and lubrication additives, have been hailed as major breakthroughs in his field. He has received numerous awards, including four R&D-100 Awards; holds 15 U.S. patents; and has published more than 260 papers,16 invited book/handbook chapters, and two edited books. His archival publications have generated more than 4,000 citations. His current research is directed toward nano-scale design and large-scale manufacturing of more advanced nanolubricants for even higher fuel economy in engines. His latest ground-breaking development has the capacity to reshape the conventional heat-treatment and thermal diffusion processes like nitriding, carburizing, nitrocarburizing and conventional boriding, which are used extensively to combat friction and wear in all kinds of machine elements.

Robert Errichello
Robert Errichello heads his own gear consulting firm, GEARTECH, and is founder of GEARTECH Software, Inc. He has more than 40 years of industrial experience. He has been a consultant to the gear industry for the past 33 years to over 40 wind turbine manufacturers, purchasers, operators, and researchers. He has taught courses in material science, fracture mechanics, vibration, and machine design at San Francisco State University and the University of California at Berkeley. He presented numerous seminars on design, analysis, lubrication, and failure analysis of gears and bearings to professional societies, technical schools, and the gear, bearing, and lubrication industries. He is a graduate of the University of California at Berkeley and holds BS and MS degrees in Mechanical Engineering and a Master of Engineering degree in structural dynamics. Bob is a member of several AGMA Committees including the AGMA Gear Rating Committee, AGMA/AWEA Wind Turbine Committee, ASM International, ASME Power Transmission and Gearing Committee, STLE, NREL GRC, and the Montana Society of Engineers. Bob has published more than 65 articles on design, analysis, and application of gears, and is the author of three widely-used computer programs for design and analysis of gears. He is technical editor for GEAR TECHNOLOGY and STLE Tribology Transactions. He is recipient of the AGMA TDEC Award, the AGMA E.P. Connell Award, the AGMA Lifetime Achievement Award, the STLE Wilbur Deutch Memorial Award, and the AWEA Technical Achievement Award.

Professor H.P. (Pwt) Evans
H.P. (Pwt) Evans is a Deputy Director of the Cardiff School of Engineering, Cardiff University, UK. He has been an active researcher in Tribology since 1977 when he embarked on post doctoral research in numerical modeling of Elstohydrodynamic Lubrication. His main research interests have been in aspects of EHL in gearing applications and he has published 120 papers in the field. He holds BSc, PhD and DSc degrees from the University of Exeter and was awarded the Tribology Trust Silver Medal in 2009 for achievement in Tribology.

Ryan Evans
Ryan D. Evans is the Manager of Bearing Fundamentals & Tribology within the Product Technology department at The Timken Company. He earned his PhD in Chemical Engineering from Case Western Reserve University, and has been a full-time R&D staff member at Timken in various roles for 10 years. Currently, he manages a team of engineers that apply expertise in bearing fundamentals and tribology to enhance Timken's analytical methods and products.

Ryan's personal contributions have been in the areas of wear, surface engineering, thin film coatings, lubrication, and advanced surface characterization. He is a co-inventor on five U.S. patents, has published more than 20 refereed technical papers, and has given numerous presentations at technical conferences in the fields of tribology and thin film coatings. Ryan actively participates on organizing committees within the Society of Tribologists and Lubrication Engineers (STLE) and was the recipient of the Walter D. Hodson award in 2007.

Jürgen Gegner
Jürgen Gegner has been employed by SKF since 2000 and is currently the Head of the Material Physics Department in Schweinfurt, Germany. He holds a Habilitation degree with venia legendi in Material Engineering from the University of Siegen, Germany, where he has been an associate professor since 2005. He defended his doctoral thesis at the Max Planck Institute for Metal Research in Stuttgart, Germany, and received a PhD degree in Materials Science from the University of Stuttgart in 1995. The Friedrich-Alexander University of Erlangen-Nuremberg, Germany, awarded him a Diploma in Physics in 1989. He is the author of two textbooks and one book chapter, the editor of a proceedings volume, and has published more than 100 papers in journals and proceedings.

Aaron Greco
Dr. Aaron Greco is a researcher in the Tribology group at Argonne National Laboratory, where he is involved in the development of lubricants and surface engineering solutions for advanced wind turbine and vehicle drive trains. Currently, he is serving as a technical advisor to the U.S. Department of Energy, Wind Power Program office, assisting with R&D strategies for advanced wind turbine drive train and reliability programs. Aaron received his PhD from Northwestern University and a BS from Iowa State University, both in Mechanical Engineering, and has received several awards for presentations of research and publications. He is an active member of the Society of Tribologists and Lubrication Engineers, where he has served on several technical committees including Wind Energy Tribology.

Bill Herguth
Bill Herguth has been analyzing and managing laboratories for testing lubricants, fuels and machine failures for almost 40 years. He is the co-founder of Herguth Laboratories, Inc. Incorporated in 1980, Herguth Labs have two state-of the-art testing laboratories in the Chicago and San Francisco areas. He has been married to his wife Kathy for 40 years and has two sons and five grandchildren.

Walter Holweger
Walther Holweger studied at University of Tübingen from 1974-1982, when he completed his doctoral thesis. From 1982-2001, he worked in Product Development and Product Management Lubrication Technologies group. From 2001-2006, he was a Technical Consultant at SKF ERC Nieuwegein. Since 2006, he has been employed at Schaeffler Technologies, Central Materials, Herzogenaurach.

Jim Johnson
Jim Johnson is a Senior Mechanical Engineer at the NREL, Golden, Colorado. Jim's responsibilities include external business development with mid-size wind turbine component

manufacturers and OEMs. He is a Department of Energy and ARPA-E FOA Prime and sub-tier proposal co-author, and a point-of-contact and team member of the Gearbox Reliability Collaborative. He also performs database engineering support and is part of the DOE Drive Train FOA research effort implementation team. In 1995, he received an NREL Staff Award for outstanding individual leadership and technical engineering support for utility-class wind turbine blade destructive and nondestructive testing. He received an NREL Staff Team Award in 1999 for designing and building the National Wind Technology Center's 2.5 MW wind turbine drive train dynamometer. In 2009, he received the NREL Staff Team Award for participation in the Gearbox Reliability Collaborative (GRC), changing the way the wind industry designs and builds wind turbine drive trains to increase reliability.

Manfred Jungk
Manfred received his PhD in Chemistry from the University of Cologne, Germany, in 1986. From 1987-1990, he was a Development Chemist and carried out lubricant formulation work for Dow Corning. From 1990-1994, he was the Technical Service Group Leader in Plymouth, Michigan, and established an application engineering laboratory for automotive and industrial lubrication. From 1995-2003, he held various global roles in management, technology and marketing of lubricants. From 2004-2011, he led Research and Development for the Lubricants product line utilizing open Innovation Concept, cooperating with universities, institutions and suppliers. He is presently the Associate Industry Scientist, Wind Energy Solutions, for Dow Corning in Wiesbaden, Germany.

Dennis A. Lauer
After attending the United States Air Force Academy, Dennis Lauer received his Bachelor of Science in Engineering degree from Penn State University. He also received his Master's in Business Administration from the same university. Mr. Lauer was the Director of Technical Marketing for Hilti Incorporated in the United States. Hilti is a construction tool and fastener manufacturer with headquarters in Liechtenstein. After that position, he became the Head of Engineering for Lubrication Engineers, an independent industrial lubricant manufacturer located in Fort Worth, Texas. Currently, Mr. Lauer is the Vice President of Engineering for Kluber Lubrication, North America L.P. Mr. Lauer is a Registered Professional Engineer in the states of Pennsylvania, Oklahoma, Texas, and Missouri and is the author of many articles for trade journals and co-author of several books on lubrication technology. He is a member of the NSPE, STLE, ASTM, AGMA, and AIST.

Jon Leather
Jon Leather is the Wind Energy Technical Manager for Castrol Industrial. He received his BS in Mechanical Engineering from Worcester Polytechnic Institute. He is an STLE Certified Lubrication Specialist with 32 years of field experience in Industrial Lubrication (with Tribol, Castrol, and BP) and more than six field years of experience in wind industry lubrication.

Johan Luyckx
Johan Luyckx is a Mechanical Engineer with 25 years experience in the domain of transmission engineering. He has been working in the wind sector at Hansen Transmissions for six years. He is responsible for root cause analysis and performance improvement plans of failures in wind gearbox transmissions. He is actively involved with the WEC/irWEA failure mode analysis via

several bearing failure cases observed in wind gear units, the first observed occurring 22 years ago.

Ajay P. Malshe
Ajay P. Malshe (PhD 1992): He is the Founder, Executive VP and Chief Technology Officer (CTO) of NanoMech (www.nanomech.biz), founded in 2002. NanoMech Inc. is a nanotechnology platform innovations global corporation. NanoMech associates ThinkSmall delivers breakthrough product innovations to improve quality of life. NanoMech has delivers breakthrough nanotech innovations, introducing nanomanufactured product platforms to market, in machining (TuffTek) and lubrication (nGlide), sustainable and biocide additives (nGuardTM) and functional nano metal powders (ElementXTM). As an inventor, Malshe has received 32 awards/recognitions, including a Fellowship of the American Society of Mechanical Engineering (ASME); voted in NanoBusiness Alliances as one of the Most Influential Nanotechnology Leaders of 2010; a nomination in Marquis Who's Who in America (2009; 63rd Edition); and a 2005 Frost and Sullivan Technology Excellence Award. He is also a Fellow of the Institute of Physics, London, UK. He has authored more than 200 plus peer reviewed publications, 13 books and book chapters, and holds 10 patents. He has an extensive track record of global collaborations with academic institutions and companies from Australia, Japan, India, Germany, and Ireland. He is a member of professional societies such as ASME, CIRP, SME, IEEE, MRS, ASEE, ASM, and IMAPS. At NanoMech, he is directing a team of world-class scientists and engineers. He is a Distinguished Professor of Mechanical Engineering and the 21st Century Endowed Chair Professor of Materials, Manufacturing Processes and Integrated Systems at the Department of Mechanical Engineering, and an adjunct-faculty member of the Microelectronics and Photonics Program at the University of Arkansas. He also is the Director of the Materials and Manufacturing Research Laboratories (MMRL; a cluster of five laboratories). Malshe leads multidisciplinary research programs in the fields of nanomanufacturing, IC, MEMS, and micro and nano device packaging and integration, and surface engineering for advanced machining. He has graduated more than 45 graduate students (PhD/MS), trained numerous post-doctoral fellows, and provided research experience to several undergraduate and high school students. His graduates work at leading organizations, such as IBM-Almaden, University of Florida, Qualcomm Technology, and Texas Instruments.

Mark McDade
Mark McDade is a project manager with NREL's National Wind Technology Center. He is responsible for the Gearbox Reliability Collaborative Database and the NREL Grid Simulator programs and is part of the 5 MW dynamometer upgrade team. Mr. McDade's background is in information systems management. He has been with NREL and its predecessor, SERI for more than 10 years.

Brian McNiff
Brian McNiff provides wind turbine testing, failure analysis, and related consulting though his company, McNiff Light Industry, based in Harborside, Maine. He holds a BS and MS in Mechanical Engineering from the University of Massachusetts Alternative Energy program. He has been involved in the wind industry as an engineer since 1979.

Art Miller
Arthur Miller is a CBM Specialist for enXco Service Corp (eSC) and has been with the company since 1998. He worked as a field technician/supervisor until 2005 when he took a position in the Quality Control department. He managed the condition monitoring of hundreds of gearboxes through analyzing oil sample results and performing internal gearbox inspections. In 2011, he transitioned into eSC's Center for Technical Excellence engineering department, specializing in the area of condition monitoring.

Les Miller
Les Miller is currently the VP of Engineering at Kaydon Bearings and has responsibility for the design, development, and application of all products. Kaydon is specifically involved in supplying pitch and yaw bearings for the Wind Turbine industry. Kaydon is North America's largest manufacturer of such bearings. Les has been active in the bearing industry for 34 years and received his BSME from Tri-State College. He has been active in the ABMA Engineering Education Committee and Bearing Technical Committee for the past 15 years. He also has been a member of the ASME Tribology Division and is a long time member of STLE. His work history includes 26 years with NSK and a total of 8 years with Kaydon in ever increasing levels of responsibility for Product Design and Application Engineering.

Andy Olver
Andy Olver worked as a materials scientist, tribologist, and transmission engineer in the helicopter industry for nearly twenty years before taking up an academic career in 1992. His interests include lubrication, fretting, rolling contact fatigue, failure analysis, gearing, rolling bearings, and tribological materials. He has published in excess of 100 papers in the field and is currently head of the Tribology Research Group at Imperial College London.

Shuangwen (Shawn) Sheng
Shawn Sheng is a senior engineer at the National Renewable Energy Laboratory (NREL). He has BS and MS degrees in electrical engineering and a PhD in mechanical engineering. Shawn is currently leading the wind turbine condition monitoring work at NREL. Under his leadership, NREL started an active investigation of various wind turbine condition monitoring techniques. Shawn also has experience in mechanical and electrical system modeling and analysis, soft computing techniques, and automatic control. He has published his work in various journals, conference proceedings, and book chapters.

Hideyuki Uyama
Hideyuki Uyama has a Doctorate of engineering and has held positions as assistant manager and research engineer with the material laboratory in the basic technology research center at NSK in Japan. He joined NSK in 1999 and has been involved in estimation of rolling contact fatigue life and development of long-life material for rolling bearings.

Paul Veers
Paul Veers is the Chief Engineer at NREL's National Wind Technology Center and was previously a Distinguished Member of the Technical Staff at Sandia National Laboratories. He has worked in the area of Wind Energy Technology for 30 years conducting research on various aspects of wind systems including atmospheric turbulence simulation, fatigue analysis,

reliability, structural dynamics, aeroelastic tailoring of blades, and the evaluation of design requirements. Paul is currently the Chief Editor for Wind Energy, an international journal for progress and applications in wind power. He has a MS in Engineering Mechanics from the University of Wisconsin and a PhD in Mechanical Engineering from Stanford University.

Q. Jane Wang
Q. Jane Wang received her PhD from Northwestern University in 1993. She taught for about five years at Florida International University. She is now a Professor in the Mechanical Engineering Department at Northwestern University. She served the Northwestern Mechanical Engineering department as the Director of the Graduate Studies Committee during 2003-2007, and as the Adviser of the ASME Student Chapter during 1998-2003. She was elected a Fellow of the American Society of Mechanical Engineers (ASME) in 2009 and a Fellow of the Society of Tribologists and Lubrication Engineers (STLE) in 2007. She is one of the awardees of the STLE 2010 Edmond E. Bisson Best Written Contribution Award and the 1997 STLE Captain Alfred E. Hunt Best Paper Award. She received a 1997 NSF CAREER Award. Her professional society work includes service as a Board of Director of STLE during 2008-2009, Chair of the 2011 ASME/STLE International Joint Tribology Conference, Chair of the STLE Annual Meeting Program Committee during 2007-2008, the Secretary of the 2005 Word Tribology Congress Technical Program Committee, and a Member of the Organization Committee of the 2007 International Symposium of Computational Mechanics.

Lavern (Vern) D. Wedeven
Vern D. Wedeven holds a PhD in Mechanical Engineering from Imperial College, London in 1970; an MS in Mechanical Engineering from the University of Michigan in 1967; a second B.S. in Mechanical Engineering from the University of Michigan in 1966; and a B.S. from Calvin College in Grand Rapids, Michigan, in 1963. He is currently the President of Wedeven Associates, Inc., established in 1988. He has held positions as the Manager, Advanced Engineering & Analysis for SKF-America from 1983–1987; and was a Materials Engineer at NASA Lewis & NASA Headquarters from 1970-1983. His honors and accomplishments include the Walter D. Hodson Award for the best paper published by author under the age of 35 in ASLE in 1975, the Captain Alfred E. Hunt Award for best paper published in ASLE (STLE) in 1979, the Arch T. Colwell Cooperative Engineering medal for contributions to the SAE Propulsion Lubricants Committee, and the STLE International Award for outstanding contributions in tribology in 2008. He has published more than 60 technical papers in the area of Tribology, more than 100 Contract Reports in the area of Tribology, and is the author of three book chapters, and holds three patents. He is a member of ASME, ASM, ASTM, STLE (Fellow), SAE; Chairman of the Gordon Research Conference on Tribology 1984; Member SAE Committee E-34 Propulsion Lubricants Committee, and chairperson of E-34C Lubricating Characteristics.

Lane Winkelmann
Lane Winkelmann joined REM Surface Engineering, Inc., in 1996 where he was a part of the Research and Development Group as a Senior Research Associate. Since leaving the R&D group, he served for four years as the Products Manager and has been in his current position as the Director of Services for the last three years. He manages three ISF® Service Centers serving the United States and European markets. During his career, he has developed numerous products

and processes for superfinishing a wide variety of alloys for both decorative and engineered surfaces. Mr. Winkelmann has co-authored several patents and has written and/or presented numerous papers on the use of superfinishing to improve gear performance. As a result of his accomplishments, this technology has been widely adopted by industries such as wind turbines, heavy equipment, motorsports, and aerospace. He received a BS from Texas A&M University in 1991 and his MBA from Tulane University in 2005.

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

DOE/GO-102012-3496 ▪ February 2012

Printed with a renewable-source ink on paper containing at least 50% wastepaper, including 10% post-consumer waste.