Please see below for the abstract and introduction of an informative paper I wrote and presented to Congressman Mike Doyle in April of 2017. At the time a tribology bill was in the process of being pushed through the House and it was my job to convince the Congressman of the current issues and need for further funding of R&D in the field of tribology issues in wind turbines.

Abstract

Wind Turbines being a major player in cleaner energy across the world, reducing the transverse effects on the environment and the economy from fossil fuels as the main provider of energy, is limited by its already short lifespan of 20 years being shortened even further by failures due to tribological effects. It was found through this report that changes and further research on enhanced engineered surfaces for main shaft bearings, leading edge erosion reduction on the blades, and better lubrication control within gear boxes can significantly enhance the efficiency of wind turbines, reduce repair and downtime costs, and ultimately reduce the cost per kW-hour for producing wind energy. Specifically, enhanced lubrication of gearboxes can allow for dynamic control of viscosity to better adapt to changing stress loads from various wind patterns and temperatures to reduce wear. Surface coating of the blades can minimize erosion and therefore maintain high aerodynamics of the system to maximize energy production. Lastly, improved engineered surfaces for the raceway and rollers of spherical roller bearings on the main shaft will negate the chance of micropitting wear and therefore minimize the failure rate of the drive system and decrease maintenance, reliability and operating (MRO) expenses for the Wind Turbine system as a whole.

Introduction

In the modern world, there is a large drive towards developing cleaner, renewable energy sources to help accommodate a growing population and promote sustainable practices for the environment. The wind energy sector, largely generated by massive turbines on wind farms, has been steadily increasing over the past few years. Although wind turbines provide clean energy and are relatively inexpensive, the penetration of wind farms around the country and the amount of energy generated is still currently vastly lower than its fossil fuel competitors. A large part of this problem is wasted energy in the generation process, due to tribological effects on a wind turbine’s extensive blades, main shaft bearings, and inner mechanisms of the gearbox. Current models of wind turbines typically have a short lifespan of 20 years. Through energy saving improvements, hopefully that average lifetime will increase in the near future.

In this report, the tribological effects will be studied through enhancing surface engineering of the main shaft bearings to reduce micropitting wear, bettering surface coating of blades to minimize erosion, and improving upon the lubricants within the gearbox. A brief analysis of these problems will be explained, followed by current research and potential solutions to some of the biggest energy-wasting issues in modern wind turbines.

Problem 1

Current production of Wind Turbines consist of two primary structures, a modular wind turbine design where the gearbox is included in the nacelle, and a direct drive design that incorporates a generator directly in the nacelle. With both structures, a main shaft is the rotating interface transferring the rotation of the blades to provide energy through the gearbox or generator. This main shaft is supported by bearings that witness a great deal of the torque and pressure experienced by the system. Due to the forces witnessed, many of these bearings experience great amounts of wear that reduce their serviceable life to much less than that for which they were designed for, causing expensive downtime and excessively high maintenance and warranty costs. [ref. Kotzakas (2010)]

Spherical roller bearings are the most commonly used bearings for supporting the main shaft of modular wind turbines. They accommodate the slight misalignments that occur between the shaft and the bearing housing well and allow for a rotatable shaft without significant resistance. These bearings however are suffering from increasing failure due to the wear they are experiencing. The main form of this wear occurs from micropitting, specifically low-cycle micropitting, which is caused by high amounts of sliding between rollers and ring raceways generating considerable shear stresses in the contact zone. These stresses cause microcracks to develop and propagate, forcing pieces of the raceway to break away from the surface and leave pits that are micrometers in size. These cracks then reduce the function of the bearings and require service which is costly and causes downtime in the performance of the wind turbines.

The opportunity for research in this field that could significantly enhance the performance of the bearings and therefore the performance of the wind turbines stem from the two main causes of these cracks. The first cause is insufficient film thickness of the lubricant between the raceway and the rollers. The second main cause comes from differences in rotational speeds between the outer and inner edges of the roller know as Heathcoat slip. To approach these topics and enhance the performance of the bearings, research on the engineering of the surfaces to reduce asperity contact and a continued barrier to the war responsible for micropitting must be conducted. Improved raceway engineering can significantly reduce micropitting and enhance the life expectancy of the roller bearings. Different finishing processes can reduce asperity length tremendously (Figure #1) and therefore even when the surfaces are rotating relatively slowly passed one another (25-35 r.p.m) a film of viscous lubricant can still provide enough of an interface that the asperities won’t come in contact and mitigates the risks of micropitting. This will reduce friction effects from the bearings which will increase the rotational efficiency of the main shaft and produce more energy from the generators, as well as reduce the failure of bearings which will lead to longer life spans of wind turbines and lower the cost per kW-hour for producing wind energy.

Problem 2

Blade tip erosion caused by friction from Rain and hail can lead to significant erosion of wind turbine blades which creates a chain reaction of negative effects. The aerodynamics and efficiencies of blades can be seriously reduced through erosion in turn decreasing Wind turbine energy production and furthermore profit are directly impacted by the speed and aerodynamics of the blades. Leading edge erosion can result in a 50% reduction in the power output of turbines. This is a significant blow to the profitability of a wind turbine if it can not produce the same level energy over the course of its lifetime (Dalili 19). In an experiment conducted on airfoils with leading edge erosion resulted in increased drag from 6 - 500% due to varying levels of erosion. An 80% increase corresponded to a 5% reduction in annual energy production once again limiting the profitability of the turbine (Chinmay 31). There is significant information out that there that supports this claim that leading edge erosion negatively impacts energy output and consequently profit.

In order to produce more power wind turbine blades are growing in length but this is coupled with an unintentional drawback. Although angular velocity remains somewhat constant with longer turbine blades the tip speed of the blade increases which can be detrimental to the leading edge of the blade. In modern wind turbines this tip speed can reach 80 m/s. Often times wind farms are located in environments that incur high winds but this increase in high wind speed is coupled with inclement weather conditions. Rain and hail contribute significantly to wind turbine erosion through high impact speeds. These particles impact at high speeds and create a shear stress with the surface of the leading edge. Due to market competitiveness literature on blade erosion is sparse. Several sources however state observations from operators. It is claimed that leading edge erosion can become an issue after only two years, another source where Rempel states that erosion can be observed after three years with the tip being the most susceptible (Gaudern 7).

The factors that can be controlled in the situation are blade length, and blade material. Shortening blade length will decrease erosion and wear while at the same time decreasing energy production. A much more effective and logical decision would be to change the material the blades are made of. This does not constitute a complete substitution in blade material but it can include a leading edge cover (i.e. tape, surface coating) or material composite design. Blades are commonly made of a composite of fiber reinforced plastic which feature a thermosetting polymer matrix that could be epoxy or polyester with reinforcing glass or carbon fibres. The blades are composed of laminates in multiple orientations consisting of biaxial or triaxial weave reinforced plies. This material is ideal for long load bearing structures. The drawback to this material although ideal for several applications of wind blades is its poor performance in impacts perpendicular to the reinforced direction.

Polytech conducted an experiment comparing different materials to cover the blade with. They created a swirling arm apparatus and water to simulate the effects of rain on wind turbines. A patented ProBlade^{TM} coating system made of a polyester based substrate was compared to that of tape and unprotected edge. In the experiment the coating system successfully resisted significant erosion. The tape effectively prevented resistance but this method requires replacement which is not cost efficient. An additional negative impact of tape is the tape increases the drag between 5% to 15% and creates unwanted noise (Gaudern 13). The unprotected blade showed significant rain erosion after testing.

To predict the pressure exerted on the surface by a liquid droplet the waterhammer equation can be used. With P as the pressure, $\rho_0$the density of water, $c_0$speed of sound through water, and V_0as the impact velocity of the water droplet and the blade. (Gaudern 23)

$$P = \rho_0 c_0 V_0$$

Now knowing the pressure the damage threshold value (DTV) can be obtained.

$$V_{DT} = c_w\, 1.41\left(\frac{{K^2}_{IC} c_R}{\rho^2 {c_w}^2 d}\right)^{1/3}$$

With $K_{IC}$is the fracture toughness of the target material in this case epoxy, $c_R$is the rayleigh wave velocity, $c_w$the compressional wave speed in the water, d is the droplet diameter and $\rho$the density of water. These values for different pressures and water droplet diameters are plotted in Figure #2 (Gaudern 28). As can be seen in this plot, epoxy can be damaged at a wide range of velocities many of which are below 80 m/s which is a realistic speed for wind blade tips. This further proves how rain, through tribology, can cause erosion on blades.

Problem 3

Due to the nature of the rotation mechanism, there is a high stress imposed on the gearboxes of wind turbines, commonly resulting in different modes of failure. Some of these failures can be avoided with sufficient lubrication of the bearings and inner pieces of the gearboxes; however, it is difficult to chose a “one size fits all” lubricant with varying stress loads and temperatures caused by different weather patterns. Improvements to lubricants can easily be made to increase the lifespan and spend less money on replacing parts by using an enhanced lubricant with reduced friction and wear properties. Recent studies have shown that dissolving carbon dioxide in an ionic liquid (IL) for use as a lubricant can allow for precise control of lubricant viscosity in order to adapt to changing loads and temperatures. This solution can ultimately increase the lifespan of the gearbox mechanism, and thus the wind turbine altogether, as well as reduce the amount of energy wasted when weather conditions are not optimal for the specifics of the design [ref. Pohrer (2015)].

In order to accommodate for the aforementioned high stresses in a wind turbine, a lubricant is necessary to protect bearings within the gearbox from wearing too quickly, but also allow for appropriate movement to generate electricity. Specifically, the lubricant must have relatively high viscosity index (VI), upon the order of 150 or higher. This value describes the influence of temperature on the viscosity of a liquid. Higher values indicate lower influence of temperature on viscosity, which is favorable. For low loads or low temperatures, a decreased viscosity is preferred to prevent unnecessary power losses and low stress on the bearing. At higher temperatures or higher loads, an increased viscosity is preferred in order to protect the inner mechanism of the gearbox from effects of friction and wear.

In attempts to improve upon the existing lubricants, studies have looked into using ILs to replace regular base oils. The are many advantages to using ionic liquids over common oils, most notably their low friction coefficients due to their chemical structure. Additionally, ILs are known to have a low vapor pressure, they are nonflammable, have high thermal stability and can conduct electricity. The ability to conduct electricity could be especially useful to deflect voltage peaks and thus prevent destruction to the bearings. From tribological testing completed that compared ILs to common base oils, the properties for friction, wear coefficients and contact angles were similar if not better. However, one of the main reasons for switching to ILs is the benefits of dissolving carbon dioxide within the lubricant.

CO_2 readily dissolves in ILs. It is also nonflammable, nontoxic, inexpensive and can easily be separated from the liquid. From the data in the paper shown in Figures #3 and #4 below, studies performed on different types of ILs as well as a few synthetic poly(α-olefins), or PAO lubricants, demonstrate that dissolving CO_2 in these liquids improves the viscosity index of each. The tests were run at two temperatures and it can be seen that there was little effect on the density, while significantly lowering the dynamic viscosity of each lubricant. Improving the resistance to temperature is already a tremendous benefit, but the ability of CO_2 to be separated from the lubricant is also extremely important because it allows for dynamic control of the viscosity of the IL. Because of this, through lowering or increasing the pressure in the gearbox, the viscosity of the lubricant can be modified to accommodate changing conditions without actually changing the liquid itself. This is significant in creating the optimal conditions for changing weather and loads on the turbine. Typically, oil in the gearboxes needs to be replaced every 3-5 years. If that time can be doubled because of enhanced lubricants, that saves money on replacement and maintenance costs. By maximizing the appropriate viscosity of the lubricant to be used, operators can save money replacing parts and ultimately through wasting less energy over time by reducing wear.

Conclusion

The effects of micropitting caused by Heathcoat slip and thin lubricant films at low rotational speeds cause major damage to the inner raceways of spherical roller bearings holding the main rotary shaft of a wind turbine and therefore fail much earlier than they are rated for. This early failure causes substantial downtime in usage of wind turbines, requires high costs for cranes and heavy machinery to replace these components, and ultimately sky rockets the MRO expenses which increases the overall cost per kW-hour and therefore reduces the competitiveness of wind turbines. To apply numerical value to this issue, data from Faulstich in 2009 (Figure #5) depicts that failure from the drive train (primarily failure through the bearings) occurs at a rate right under .2 per year or about once every five years. With most wind turbines having a life expectancy of twenty years or greater, the bearings would on average need repair four times over the course of the wind turbines life. These repairs and replacements have proven catastrophic for the profits of certain wind farm companies, such as was reported by CEO of Siemens AG Joe Kaeser in 2014 stating that the company reported a loss of €50 million, mostly as a result from bearing issues. The research in effective surface engineering to increase hardness and reduce frictional effects on the contact surfaces of main shaft bearings is therefore essential for the enhancement of wind energy in our nation and across the world.

When viewing the issue of blade erosion in wind turbines it is important to note that this is a critical problem especially in Pennsylvania where there is an inclement weather. In order to improve the lifespan and efficiency of wind turbines leading edge erosion needs to be minimized. It can be minimized by surface coating the blade, altering the material of the blade, or tape. Tape however is costly due to replacement and its added drag to the system reduces energy production. Changes in the material are possible but these could reduce the favorable strength and density which current blades possess. A surface coat is the most realistic solution to this issue. By protecting the material underneath that is more susceptible to erosion the blade can stay intact. If erosion is minimized the aerodynamics of the system will remain high furthermore increasing energy production and furthermore profit.

High viscosity indexes of lubricants in the gearboxes of wind turbines are critical to help lower the amount of power lost, ensure reliability of the turbine and promote longevity. There is a need to develop a better lubricant with a longer lifespan and enhanced flexibility to environmental conditions. Recent studies have shown ionic liquids to have lower friction coefficients and wear rates compared to regularly used base oils. Studies have also shown dissolved carbon dioxide in lubricants lowers viscosity and thus is an improver of the viscosity index, as well as being easily separated from the liquid. Combining both of these results enables turbine operators to control the viscosity of a IL-CO_2 lubricant by controlling the pressure of the gearbox. Increasing the pressure will lower the viscosity, which is desirable at low loads and temperatures from variable wind and weather conditions. Decreasing the pressure will increase the viscosity which is preferred for higher loads and temperatures. Therefore, operators can tailor the lubricant without physically changing it to save energy and money.

Figures

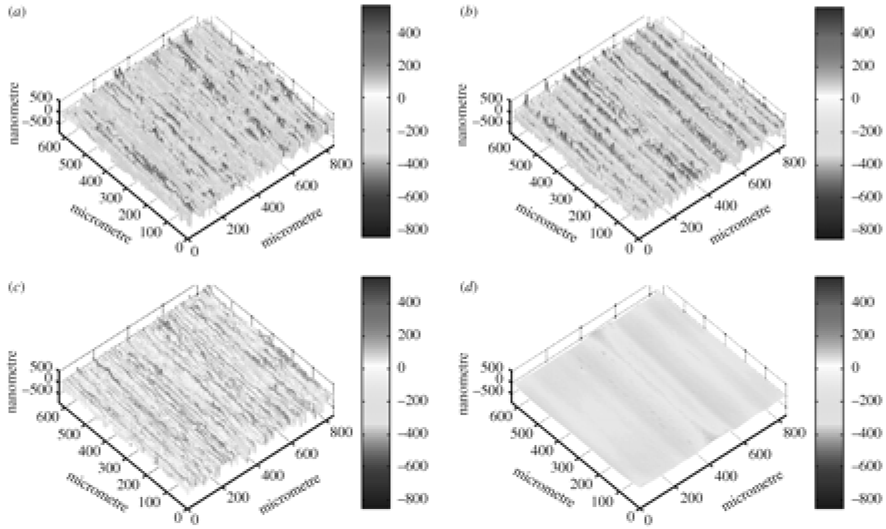

Figure #1. Surface textures from an interferometric white light microscope. (a) Bearing raceway assembled with traditional steel rollers measured pre-test; (b) bearing raceway assembled with traditional steel rollers measured post-test; (c) bearing raceway assembled with smooth, isotropically finished, MC/aC : H-coated rollers measured pre-test; and (d) bearing raceway assembled with smooth, isotropically finished, MC/aC : H-coated rollers measured post-test.

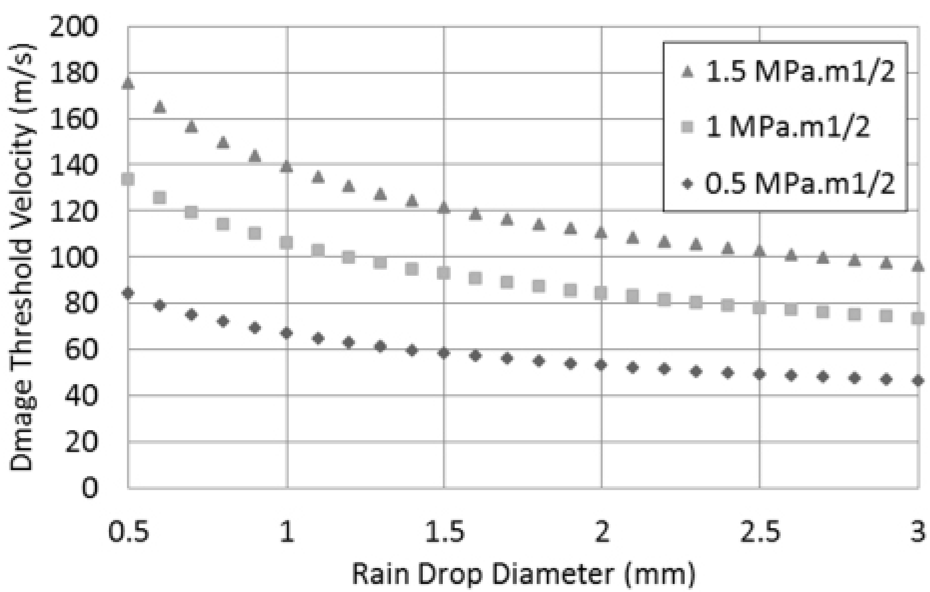

*Figure #2. Damage threshold velocity for rain drop impact on an epoxy target across a range of droplet diameters and for different epoxy fracture toughness values (*Gaudern *28).*

Table 5. Density, Dynamic Viscosity, and Viscosity Index with Dissolved CO_2

	Density (g cm^{-3})		Dynamic viscosity (mPa s)		
	at 313 K	at 373 K	at 313 K	at 373 K	viscosity index, VI
[OMA][DMP]					
0.1 MPa (ambient pressure)	0.928	0.892	468.00	25.30	100
0.5 MPa (CO_2 saturated)	0.932	0.893	320.70	21.50	117
1.0 MPa (CO_2 saturated)	0.933	0.894	281.30	21.60	132
[BMPyrr][DBP]					
0.1 MPa (ambient pressure)	1.013	0.975	445.30	32.90	117
0.5 MPa (CO_2 saturated)	1.016	0.975	351.30	23.00	112
1.0 MPa (CO_2 saturated)	1.018	0.977	328.90	22.90	118
[MEG$_2$MPyrr][B(MEG$_2$)P]					
0.1 MPa (ambient pressure)	1.141	1.100	106.38	15.97	162
0.5 MPa (CO_2 saturated)	1.141	1.098	96.16	15.14	168
1.0 MPa (CO_2 saturated)	1.141	1.097	90.23	14.97	178
PAO-8					
0.1 MPa (ambient pressure)	0.821	0.780	39.52	6.51	149
0.5 MPa (CO_2 saturated)	0.822	0.781	34.60	6.26	167
1.0 MPa (CO_2 saturated)	0.824	0.782	30.08	5.95	183
PAO-40					
0.1 MPa (ambient pressure)	0.833	0.800	311.28	34.00	168
0.5 MPa (CO_2 saturated)	0.836	0.801	253.36	32.21	187
1.0 MPa (CO_2 saturated)	0.837	0.801	219.64	30.53	198
PAO-mixture					
0.1 MPa (ambient pressure)	0.832	0.795	234.16	27.57	170
0.5 MPa (CO_2 saturated)	0.834	0.797	205.42	26.21	179
1.0 MPa (CO_2 saturated)	0.835	0.798	180.30	25.72	194

Figure #3. Results of various tests on the density, viscosity and viscosity index for each of the lubricants with various pressures of CO_2 dissolved. The first three listed compounds are ionic liquids (ILs). The second three are various synthetic poly(α-olefin) compounds (Pohrer, 2015).

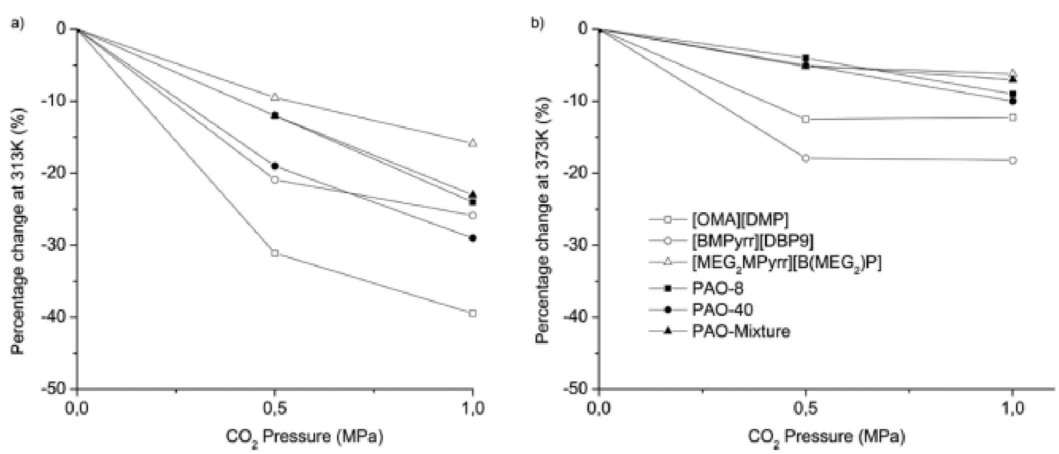

Figure 8. Change of dynamic viscosity with dissolved CO_2 at (a) 313 K and (b) 373 K.

Figure #4. For the tests ran in the previous figure at the two temperatures, a visual representation of the effect of CO_2 on viscosity in percentages. (Pohrer, 2015).

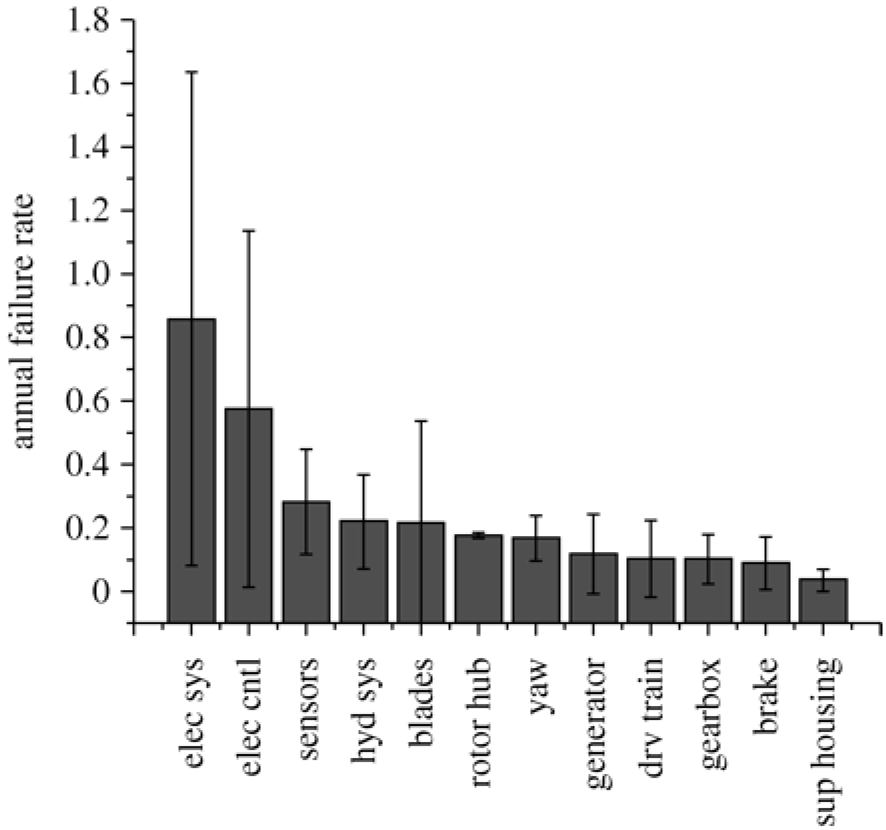

Figure #5. Data from Faulstich et al. (2009), displayed with error bars of 1 s.d., illustrate that the systems containing tribological components typically associated with wind turbine reliability—the pitch, yaw, generator and gearbox systems—experience fewer than 0.2 failures per year.

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Glossary

Aliphatic -- (adj). describing an organic cyclic compound in which the carbon atoms form open chains; this is a classification opposite to an aromatic hydrocarbon that forms rings

Boundary tribofilm formation -- (n.) refers to the development of a tribofilm on the edge of a material; a tribofilm is a ‘third body’ made up of a different chemical composition and structure as the material it is in contact with, that has significant effects on the friction behavior and wear performance, and is generated through sliding contact

Fugacity -- (n). a chemistry term describing the effective partial pressure of a chemical equilibrium constant, replacing the mechanical partial pressure; the fugacity of a gas is equal to the pressure of an ideal with the same chemical potential of the real gas in consideration

Hertzian fatigue -- (n.) refers to the fatigue (weakening of the material due to repeatedly applied loads) generated from Hertzian contact stress that is produced when two curved surfaces come in contact and deform under the appointed loads and is commonly seen in gears, as in the context of this paper

Micropitting -- (n.) is a fatigue failure of the surface of a material commonly seen in rolling bearings and gears.