RESEARCH VISION

Research on the Mechanisms and Treatment of Electrically Induced Bearing Damage (EIBD)

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This document describes the potential for research of the fundamental mechanisms governing the electrically induced bearing damage (EIBD). The principal source of EIBD is due to plasma arcing occurring on rolling element bearings and other lubricated mechanical components. Tribological and electrical contacts are an integral part of every mechanical system and their reliable performance is essential. This has become increasingly important for electric vehicles where electrified mechanical components (bearings and gears), in addition to many other connectors in the drive system, must perform reliably. Several studies have found that stray or leakage currents could cause pitting (i.e. electrical discharge machining) in bearings [1-3], including the first three year of our study that employed silver, carbon and iron-oxide nano-particles to improve performance. If an electric current is applied to a mechanical component, such as a gear or bearing, a non-conductive lubricant film can allow charge to build up eventually leading to arcing or discharges across the film. These processes cause pitting damage on the surfaces, accelerating the occurrence of failure. The PI would build on already synthesized models of electrical contact created at Auburn University [4-9]. The PI's initial experimental results have also produced pitting damage in a controlled manner and shown that silver nanoparticle additives reduce the occurrence of electrical discharge (arcing) pitting more than other lubricants [10-12], but the mechanism at work is still not completely understood.

A possible project would be to create a robust model of electrical arcing across relatively non-conductive films in mechanical contacts will be constructed. The model would allow for the analysis of what electrical and mechanical conditions facilitate arcing between the surfaces. This requires the consideration of electrical and thermal fields along with fluid and solid mechanics. In addition, the films and surface roughness are on the micrometer and even nanometer scale. At small scales not only can the material properties deviate from their values at the macro-scale, but quantum mechanics can play a role. The resulting model would allow the mechanisms at work to be analyzed so that they can be controlled or avoided. This could be achieved by using alternative lubricant additives or coatings. Details about the possible modeling and experimental measurements, along with a background and preliminary results are provided in sections 1-4.

1. Background

Electric vehicles continue to grow in usage which also brings into focus their tribological performance and reliability[13]. In the case of electric vehicles there is growing concern about the performance and reliability of mechanical components such as rolling element bearings and gears[14]. This is due to not only increased temperature and speed expectations[14] but also because of potentially damaging electric currents flowing across the surfaces[2, 15, 16]. Stray electric currents and charges can build in several ways in machinery, and the accumulation of a large charge can induce arcing across the lubricating film. Arcing yields a plasma that melts and vaporizes the metal surfaces, causing what is termed EIBD and electrical discharge machining (EDM). As a consequence, small surface pits and other surface damage can occur that can lead to surface fatigue and eventual failure if the bearing is operated continuously[17]. The surface damage can also cause mechanical components to emit undesirable noise. In addition to rolling element bearings, this can also occur in hydrodynamic sliding bearings[18]. Grease is also desirable in many applications to reduce the possibility of lubricant leakage[19].

2. Theoretical Model

The PI, Prof. Jackson, has already made progress in theoretically modeling lubricated and unlubricated electrical contacts [6-8, 20-22]. A possible project will build on these and other theories in the literature to develop a model of electrified lubricated rolling bearing contacts to predict EIBD. The ultimate aim could be that the model allows for insight into the most important mechanisms at work and predicts the initiation of arcing. The main components of the proposed model are introduced here. The parts of the model are organized into modules for clarity. The explanations provided do not include all of the necessary equations and mathematical details.

2.1 Electrical Arc Initiation

This is probably the most unique part of a possible model. First, the occurrence of arcing will be predicted based on the dielectric breakdown voltage of the oil. Dielectric breakdown strength is considered to be a material property that describes when a relatively non-conductive film breaking an electrical circuit will collapse and allow a material to ionize and conduct electricity. When the material ionizes, usually at high temperatures, it becomes a plasma. Plasma is another phase of matter similar to gases, except the electrons are no longer connected to an atom. The arc formation in oil is initiated first by the oil ionization The dielectric breakdown strength of mineral oil is 10-15 MV/m[23]. The property provides the strength or resistance to electrical breakdown per thickness of the material. Since the film thicknesses of typical elastohydrodynamic rolling element bearings are on the order of nanometers or micrometers, the voltage required for the initiation of an arc is on the order of Volts. This makes arc initiation more feasible from the voltages expected from leakage or stray currents in an EV or other electrified machines.

In addition, since the oil film thickness of typical rolling element and gear contacts can be on the order of nanometers, this makes them susceptible to the quantum mechanism of electron tunneling [24]. Electron tunneling is a mechanism by which electrons can travel across a non-conductive film with less energy than required on a bulk scale due to its wave behavior. This tunneling is often known as Fowler–Nordheim (F–N) tunneling or electron emission. It can occur even into the micrometer film thickness range. The initial tunneling of electrons through the film allows a gas streamer and eventually a plasma arc to form. Therefore electron tunneling can lower the effective dielectric strength of the oil. This can be accounted for by adjusting the dielectric breakdown voltage with the Paschen curve[25]. In the proposed work this will be predicted between rough surfaces separated by a thin film and therefore the curvature of the asperity tips will also be accounted for as in [26]. This electron tunneling model is similar to a previous work of the PI on anisotropic conductive films. Conductive particles are mixed into a non-conductive epoxy resin adhesive and compressed between two surfaces. The epoxy is not completely evacuated from between the conductive particles and so the conduction between them is governed by electron tunneling. Existing predictions of arc pitting damage from the circuit breaker field will be employed to predict wear [27].

2.2 Mixed Lubrication Modeling

In the mixed lubrication regime, the thickness of the lubricant film is thin enough that the roughness of the surfaces influences the fluid flow. To consider the influence of roughness on the lubricant flow, Patir and Cheng [28, 29] derived a modified form of the Reynolds Equation:

$$\frac{\partial}{\partial x}\left(\phi_x \frac{h^3}{12\mu}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(\phi_y \frac{h^3}{12\mu}\frac{\partial p}{\partial y}\right)=v_x\frac{\partial h}{\partial x}+\frac{\partial h}{\partial t} \tag{1}$$

where ϕ_x, and ϕ_y, represent the rough surface flow factors that incorporate the fluid flow obstruction. Alternatively, the Reynolds equation could be solved deterministically for measured nano-scale rough surfaces. Note that the flow factors approach unity for increasing film thickness and therefore, the modified Reynolds equation (Eq. 1) becomes the conventional full film Reynolds equation in those cases. The fluid pressure between the surfaces is found by numerically solving the modified Reynolds Equation (Eq. 1). In the diverging areas of the film thickness the pressure can decrease and their cavitation is considered with the Reynolds boundary condition (pressure has a lower limit of zero).

If external load increases or velocity decreases the surfaces will be pressed together so that the solid surface asperity contact area will increase. Therefore the model will incorporate an established statistical elastic-plastic asperity contact model to consider contact between the rough surfaces in close proximity. Although not outlined here, the research may also explore the use of multiscale and fractal rough surface contact models. The statistical model assumes a statistical distribution, $\Phi(z)$, for the asperities on the surfaces and then considers those above the mean height between the surface peaks, *d*, to be in contact. Each asperity is represented by an elastic-plastic contact model that includes the transitions from elastic to elastic-plastic and fully-plastic regimes, and variations in the fully-plastic pressure[30]. This statistical model, first proposed by Greenwood and Williamson, and here used with elastic-plastic asperities is given as:

$$P(d)=\eta A_n\int_d^{\infty}\overline{P}_F(z-d)\Phi(z)dz \tag{2}$$

The statistical model is also used to predict the solid electrical contact resistance between the rough surfaces due to the constriction of the isolated asperities. However, note that conduction can also occur across the film and will be considered. Greenwood and Williamson again provided this in their original work, except now the elastic-plastic asperity model is used to calculate the asperity contact radius, *a*. The constriction or spreading electrical resistance at each asperity is predicted by the Holm theory, which assumes that these contacts are isolated from each other. Then the equation for electrical contact resistance between statistically rough surfaces is:

$$\frac{1}{Er_{ep}(d)} = A_n \eta \int_d^\infty \frac{2a_{ep}}{\rho_L} \cdot \Phi(z) \cdot dz \tag{3}$$

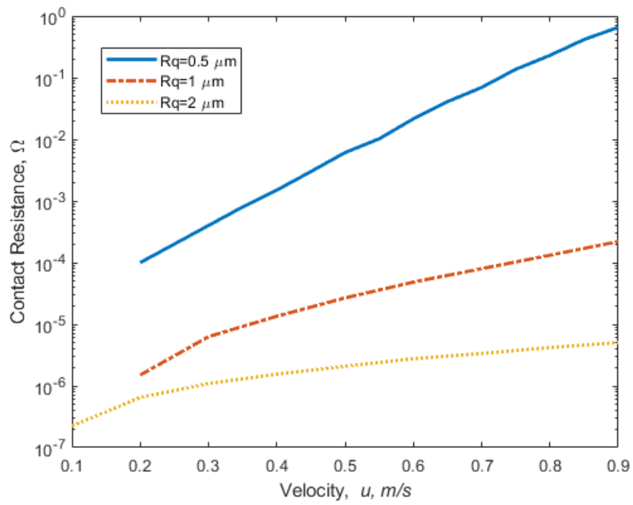


Figure 1. Predicted mixed lubrication contact resistance as a function of velocity also considering various values of effective surface roughness.

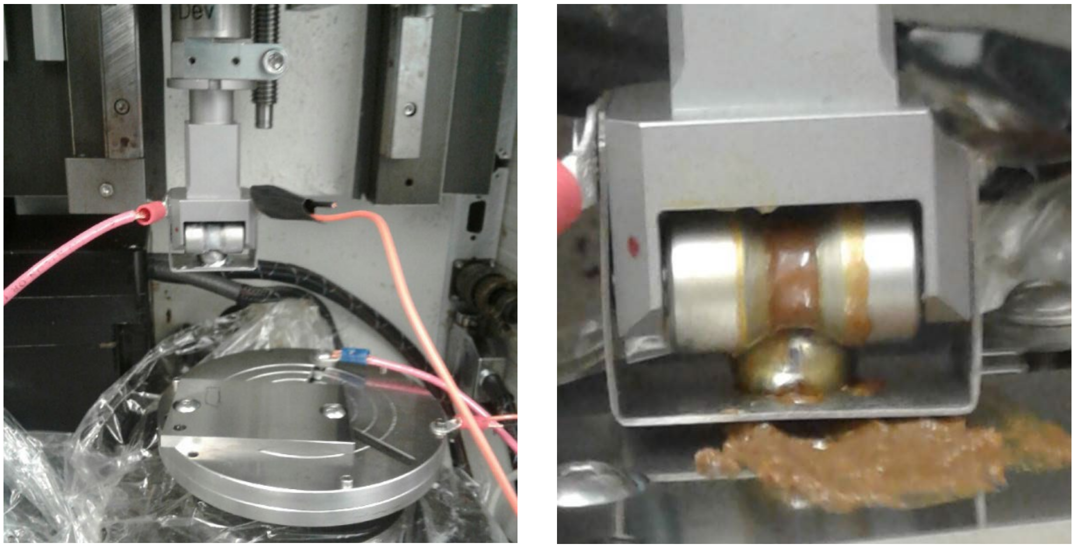
Based on this methodology briefly outlined here, but more thoroughly in [6, 7, 20, 21, 31], the contact resistance is predictable as shown in Fig. 1. This demonstrates the first step toward building a model capable of analyzing the electrified tribo-mechanical component behavior. The model predicts that as relative velocity between the surfaces increases, a lubricating film is formed that increases the electrical contact resistance. Also predicted by the model is that increased roughness helps to maintain solid contact and reduces contact resistance.

Furthermore, previous studies by the PI considered the contact modeling of rough surfaces with solid particles in between them[20] and of particles within a non-conductive medium, similar to lubricants[8]. These different parts will be incorporated together into a robust model of lubricated and electrified contacts.

3. Electrified Rolling Element Testing

A possible project could employ an electrified rolling ball on disk test developed for the preliminary findings of the project. Additional measurements could also be performed at other locations. The rig was initially configured for reciprocating motion to improve contact resistance measurements because the test leads will not have sliding contacts. Although this might capture start-stop conditions in EV rolling element bearings, a longer unidirectional test will be essential to evaluate practical vehicle driving conditions.

Rolling sphere-on-disk (i.e. ball-on-disk) friction tests were set up using a Bruker-UMT3 Tribotester (see Fig. 2). The electrical contact resistance will be measured during the test using an Agilent 34410A multimeter. A power supply is also connected to the samples in parallel and is able to apply a controlled voltage or current through the components. This could be considered a 4-wire resistance test measurement as is common in the electrical contact literature. A heating element is used to provide an additional load on the circuit. In this way, we can test rolling elements bearings under controlled electrical and mechanical loads.



(a) (b)

Figure 2: Photographs of the test setup and fixture before and while testing grease.

In addition, testing contacts with varying lubricants, additives, coatings, and surface finishes will help to determine the mechanism at work. Different post-experiment analyses will be performed to explore the nature of the arc surface damage using standard techniques such as SEM, EDX, AES, XPS, etc.

4. **Recent Work**

Recently, the PIs successfully demonstrated that silver, carbon black, and iron-oxide nanoparticles in grease improve significantly the performance of rolling balls on flat contacts under a damaging electrical load [32-34]. In addition, in recent studies the boundary of the loads, speeds and other conditions that allow for damaging discharges have been explored, but more work is required[35]. The studies initiated with the synthesis of Ag nanoparticle colloids suspended in hydrocarbon oil and then blended into polyurea grease. One of the main contributions of the investigation was also setting up the novel electrified tribological test which can now be used to evaluate other lubricants under electrified conditions. Our tests and other recent studies show that the current flow accelerates surface degradation via small-scale arcing across lubricating films. The arcing induces microscale pitting of the surfaces (see Fig. 3). The results from our study suggest that Ag and perhaps other metallic nanoparticle additives in lubricants may be useful to improve the performance of these contacts. Such study included silver nanoparticle-enhanced greases, along with base and fully-formulated oils for comparison purposes. Our data indicated that a reduction in pitting from arcing occurred in the presence of nanoparticles (see Fig. 3 and 4), although oils with other additives also appear to exhibit an enhanced performance, but to a lesser degree. The mechanism responsible for the improvement remains unknown and its determination will be a focus of the proposed work.

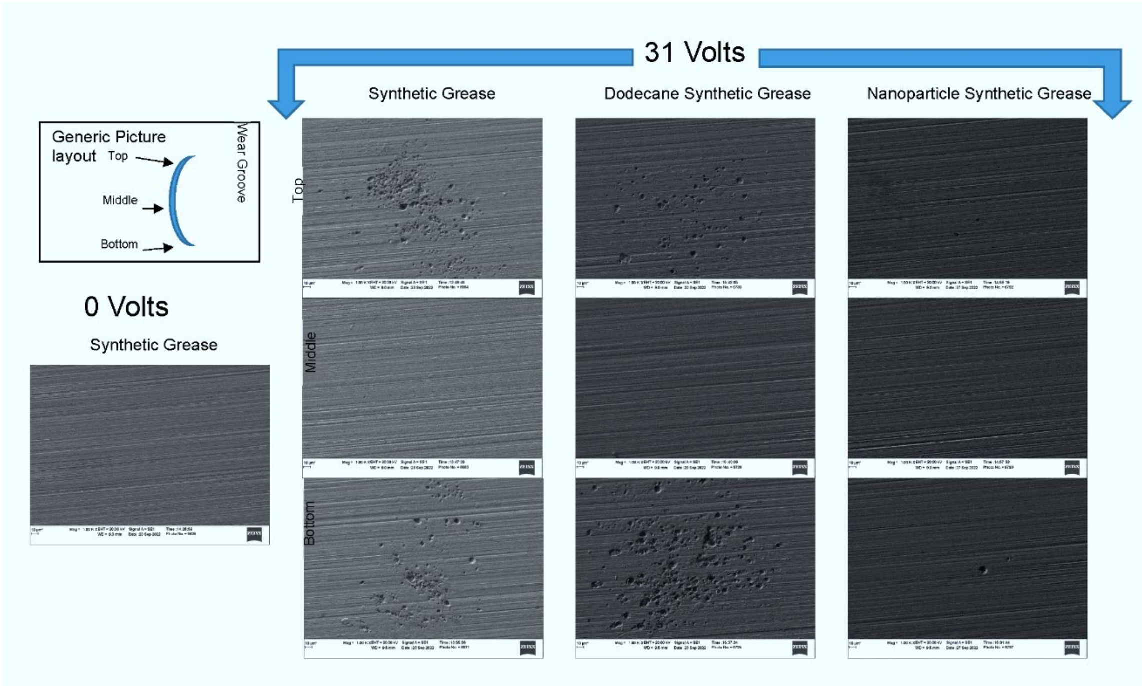


Figure 3: Image analysis of SEM of electrically pitted synthetic grease samples.

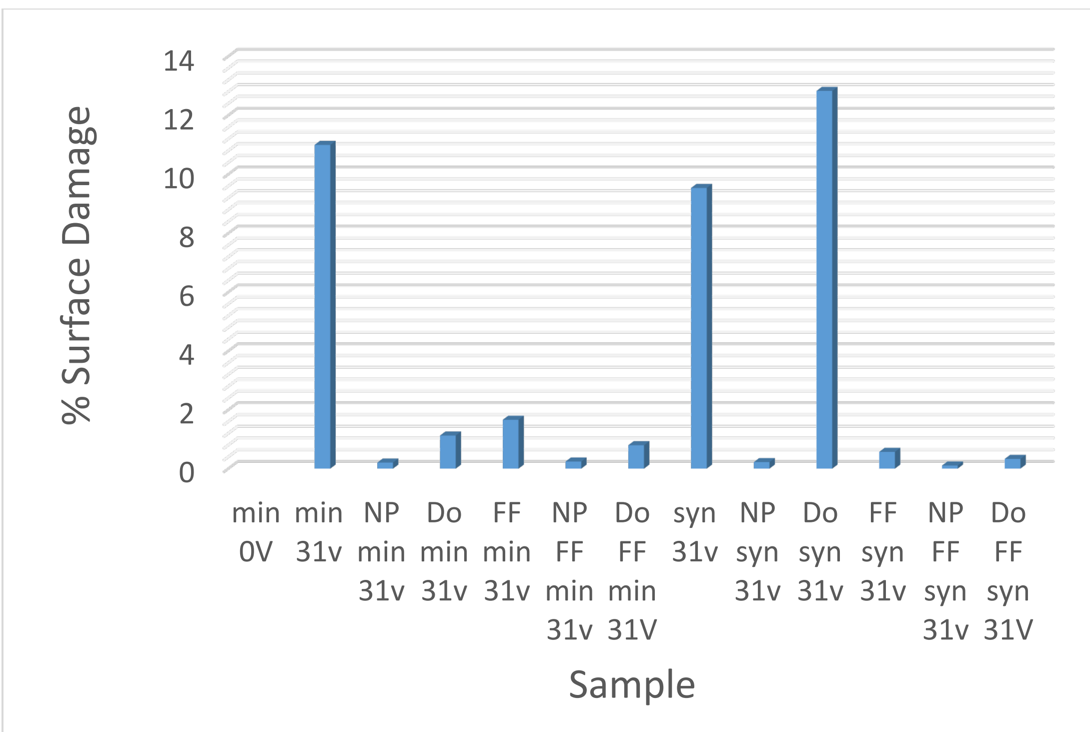


Figure 4: Percentage of surface damage for flat substrates in preliminary tests with different samples when different greases.

Plotted in Fig. 4 are the results obtained by analysis of the images illustrating the damage of the substrates derived from electrical pitting of the surface. First, the image analysis clearly indicated that the highest surface damage induced by electrical pitting took place in experiments that employed unmodified synthetic and mineral greases. Tests run with synthetic grease mixed with dodecane also yielded a larger percentage of surface damage. Experiments with the four greases containing Ag nanoparticles (dodecane colloid) yielded the lowest percentages of surface damage, supporting earlier conclusions. Furthermore, most experiments with dodecane and fully-formulated greases yielded less surface damage as compared to tests with unmodified greases, but in differing degrees.

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