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REVIEW

Tribological Behaviour of Smart Fluids Influenced by Magnetic and Electric Field – A Review

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A B S T R A C T

This review paper highlights the tribological behaviour and performance of smart fluids. Two main kinds of smart fluids, that respond to a suitable external stimulus are investigated – electrorheological and magnetorheological fluid. The excitation of an external active field significantly increases or decreases the fluidity, depending on the fluid type. First, the tribological behaviour of both types of smart fluids without the influence of an external field and under the external active field, respectively, are reviewed. Subsequently, the influence of external field activation on the lubricating layer is described. Finally, a summary of the most notable findings of investigated smart fluids performance and behaviour is provided. Possible future applications are then considered for smart lubricants technology and engineering devices.

1. INTRODUCTION

In the last decades, there has been an effort to minimize the lubricant film thickness of mechanisms, because of the lower friction and less energy consumption. The optimum performance of a mechanism is strongly dependent on the lubrication of contact surfaces to minimize the friction and wear. Thin film lubrication with respect to severe operational conditions can lead to lubricating film breakdown and consequently, the increase of contact pressure and friction and eventually the increase of wear caused by direct surface interaction. Using the conventional lubricants, it is not possible to control film thickness according to its operational conditions or apply this lubricant for e.g. compressors, bearings, valves and sealing elements for 100 % oxygen environments. Therefore, there is a desire to secure the controllability using an unconventional lubricant, such as smart fluid [1]. There are numerous fluids that can be called as “smart”, however, this paper is focusing on the fluids influenced by magnetic and electric field. Since the requirements for efficiency of conventional parts and mechanical components, such as bearings, valves, clutches etc. are still growing [2], it is necessary to look for new solutions that could meet the higher requirements. Thanks to the ability to change rheological properties by external influence, the smart fluids are liquids, emulsions or two-phase suspensions made of liquid and solid phase [3]. A base fluid, mostly consisting of oil with additives, forms the disordered liquid phase and the solid magnetically ordered phase is made of microscopic particles dispersed in the base fluid. Without stimulus of the external active field, smart fluids show Newtonian behaviour, while in the presence of a suitable external field, a noticeable increase of yield stress occurs because of particle response to excitation. Eventual, the flowing of the smart fluid is possible after achieving a certain value of yield stress which is characteristic for Bingham fluids [4].

Such behaviour in combination with the full controllability of rheological properties of the smart fluid could be a new basis of the creation of smart parts and improvement of tribomechanical systems [2]. The main objective of this paper is to review the tribological properties of smart fluids to investigate its possible of application in the future smart mechanisms.

2. SMART FLUIDS INFLUENCED BY MAGNETISM

A smart fluid is a magnetorheological (MR) fluid that is excited by an external magnetic field [5]. Such fluid consists of the base oil, additives and ferromagnetic particles. In absence of the magnetic field, the MR fluid is viscous, heavy, and shows Newtonian behaviour. As soon as the magnetic field is activated, magnetic particles are forced to create a chain structure between exciting poles. The process of chain creation lasts only a few milliseconds and is fully reversible [6,7]. This short response time allows very quick change of rheological properties of the fluid, what is already being used in various applications, e.g. dampers, clutches, brakes etc. [8-13].

Therefore, smart fluids influenced by magnetism have two phases. The liquid phase of MR fluid and the solid phase of MR fluids, respectively.

The base fluid is chosen according to the desired tribological and rheological properties. Moreover, the base fluid should be chemically compatible with particle as well as the device materials. The temperature range of MR fluids is limited by selected base fluid, mostly between – 40 and + 150 °C [14]. Available base fluids are often silicon, mineral, paraffin or hydraulic oils, silicon copolymers, water, and esterified fatty acids. A preferred base fluid is polyalphaolefin (PAO), because of its good compatibility and the relatively wide operational temperature range [15].

The liquid phase of MR fluid can be modified by various additives to achieve the best possible performance in given application. In the case of MR fluids, the most important additives are surfactants for improving surface properties of particles and stabilizers that keep particles diffused and reduce sedimentation. According to Rich [16] it is possible to reduce the sedimentation ratio of MR fluid after mixing in synthetic clay, which shows a growth of yield stress with aging.

The solid phase of an MR fluid consists of ferromagnetic particles, reacting to the presence of magnetic field. The size of ferromagnetic particles ranges between 1 to 100 μm [17]. Particles larger than 100 μm might cause jamming in devices and increase of friction and wear. On the other hand, particles smaller than 1 μm are not able to create as high resistance to flow as larger particles [15]. Such fluids with particles smaller than 1 μm (mostly around 10 nm) are also called ferrofluids. This type of MR fluid keeps the flowing form even when subjected to the stronger magnetic field. Because of this unique property, ferrofluids are suitable as a sealing medium for dynamic seals [18,19].

Particles dispersed in MR fluids are mostly spherical, because of the longer durability, lower friction and magnetic anisotropy. Except spherical particles were applied suspensions with cone [20] or flake-shaped [21] particles and polymerized chains [22]. These chains reportedly exhibited higher resistance to flow, even when subjected to magnetic field, what might be caused by creation of more complex fluid regarding to friction. The main disadvantage of polymerized chains is its slower response to magnetic field stimuli, than spherical particles, because of the lower magnetization of polymerized chains. Mostly used MR suspensions are made of one type of magnetic particles, nevertheless, there are already applied bimodal suspensions formed by different sizes of particles. Viota [23] combined particles size of 1.5 μm and 8 nm in one MR fluid. According to results of experiments, such combination had slightly better stability of colloid mixture and lower sedimentation rate. Commercial MR fluids consist of 20 to 48 wt.%

of particles. With the density from 2300 to 4120 kg·m^{-3} depending on the number of dispersed particles, the MR fluid is a much heavier fluid than pure oil [24]. The solid phase should exhibit relatively high magnetization saturation, up to 2 T [15]. Particle materials are often pure iron and iron alloys, carbonyl iron, iron oxides, nickel, cobalt etc. [8]. Most used solid phase of an MR fluid are pure iron and carbonyl iron, which exhibit relatively high magnetization saturation, around 2.15 T, while the cost is low in comparison with other potential materials [3].

An alternative way to analyse the characteristics and behaviour of MR fluids is using the mathematical analysis. Combining the knowledge of MR fluids and the experimental results provides the foundation of the mathematical equations describing the function of an MR fluid. There were several papers that dealt with the preparation of computing models of MR fluids with response to magnetic field intensity, describing system of constitutive equations for an isotropic MR fluid and a new rheological model for MR fluids that fits the experimental data and can be implemented to CFD analysis [25-27]. Another study proposed a constitutive model for shear yield stress of MR fluid, that considers the material of MR particles and the stimulus applied [28]. The results show, that the developed state transition equation (STE) shows a good agreement with the experimental results of listed MR fluids.

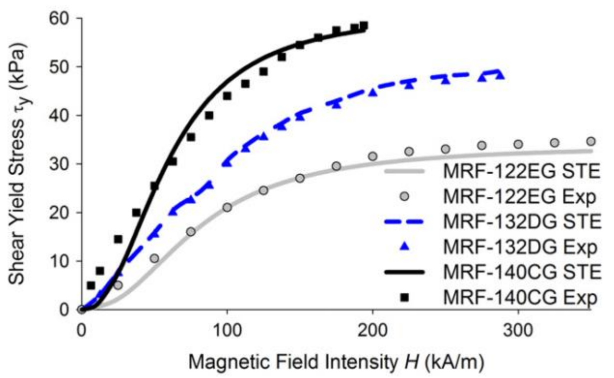

Fig. 1. Comparison of experimental and predicted shear yield stress by constitutive model (under licence CC BY 3.0) [28].

Such model can be implemented in FEM analysis software which could be helpful while designing new MR devices [28].

3. TRIBOLOGICAL BEHAVIOUR OF MAGNETIC FLUIDS

Particles dispersed in base fluid might cause various types of wear depending on the loading regime and component design. In the case of MR fluids, the most significant wear is abrasive, eventually leading to the erosive wear of contact surfaces, thus to understand those negative effect is essential for minimizing and preventing damage. Therefore, it is also important to understand MR fluids in absence of magnetic field as well as to examine in the presence of magnetic field.

3.1 Tribological behaviour of non-activated magnetic fluids

Previously, several studies focused on the examination of magnetic fluids without activation of an external magnetic field were introduced. The results of an experimental study dealing with the colloidal stability show, that a small amount (around 6 wt.%) of nanoparticles (8 nm diameter) in MR fluid of microparticles (1.45 μm diameter) can reduce the sedimentation rate. However, the height of the sediment increases with the number of nanometer-sized particles [23]. Another study shows that MR fluid with 20 to 40 wt.% of spherical particles with diameters of 1 to 5 μm can result in a lower friction coefficient than its base oil [29]. The behaviour of MR fluid is very similar to its base fluid, however, as soon as a larger number of particles gets into the contact area, abrasive wear occurs due to clustering of particles. The extent of damage is more significant with the increasing size and quantity of dispersed particles. A comparative study was done by Shahrivar et al. [30], where two types of MR fluids were examined in a point contact with pure sliding – a ferrofluid containing nanoparticles of 5.5 wt.% and a MR fluid with microparticles of 32 wt.%. The results show, that microparticles perform better at very low sliding speeds to 1 mm·s^{-1}, however, with increasing speed, the friction coefficient increased significantly. Nanoparticles showed opposite effect. As the sliding speed increased up to 1000 mm·s^{-1}, the friction coefficient decreased to approx. 25 % of its initial value as it is shown schematically in Fig. 2. This behaviour was reportedly caused by a lower concentration of nanoparticles at a higher speed, thus smaller amount of partial friction contacts.

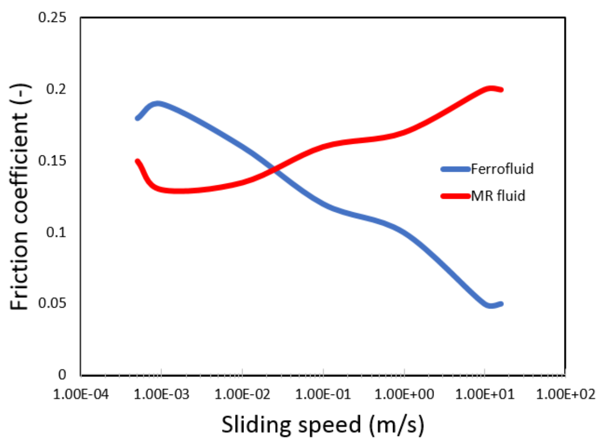

Fig. 2. Comparison of Ferrofluid and MR fluid performance.

3.2 Tribological behaviour of activated magnetic fluids

Although there were noticeable effects in tribological properties of MR fluids without the presence of magnetic field [29,31,32], the activation of external field might significantly modify performance and behaviour of the magnetic fluid [33]. Magnetic field forces dispersed particles to form chains according to magnetic flux, which leads into increasing of the apparent viscosity of MR fluid as shown in Fig. 3 [34].

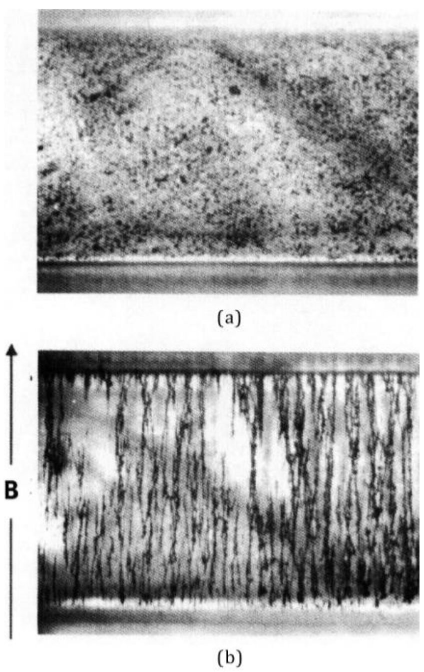

Fig. 3. MR suspension before (a) and after applying a magnetic field (b) (reprinted with permission from John Wiley & Sons, Inc.) [34].

The MR effect can be increased with increasing magnetic field intensity. Because of this ability MR fluids can be used in the finishing process of surfaces [35-37]. By using this process, very smooth surfaces with minimal damage can be achieved, since there is no direct contact of tools like that presented in a conventional machining, only rotating magnet creating permanent magnetic field. The dominant mechanism occurring during a finishing process is the abrasion. By adjusting the size of abrasive medium, magnetic field intensity and speed of rotating magnet, surface roughness Ra lower than 0.05 μm without the appearance of surface or subsurface defects can be achieved [37].

To obtain tribological characteristics of MR fluids, especially coefficient of friction and wear rate, a pin-on-disc tribometer was applied in several studies [38-40]. These characteristics were measured both with and without the use of external magnetic field. The disc was placed in the electromagnet and the contacting interface was immersed in the MR fluid [38]. Activation of magnetic field caused a decrease in coefficient of friction in case of magnetic fluids containing 6 to 35 wt. % of particles, explained as result of formation of a protecting film created by nanoparticles adsorption on contact surfaces [39,40]. As for MR fluids with the content of particles 72 to 86 wt.% the results were different [41]. Such relatively high content of magnetic particles creates the excessive growth of yield stress, that leads to the increase of friction coefficient [42,43]. As it is shown in a study [17], the dynamic yield stress exhibited an increase with the volume fraction of magnetic particles. The influence of non-homogenous magnetic field was examined by Shahrivar [44] in a compliant polymer contact lubricated by ferrofluid. They found a noticeable reduction of friction by modification of magnetic field distribution through a moving magnet under the contact area. This phenomenon was confirmed experimentally, as well as by simulation, which achieved a similar trend and values of friction coefficient.

Besides the amount of solid phase, frictional characteristics can be modified by adjusting surfaces surrounding the MR fluid. Such modification is achieved by texturing lubricated contact surfaces [45]. The change in surface profile causes the lubricant to be kept in the contact area, thus the dimples act like reservoirs.

Table 1. Summary of experiments – magnetic fluids.

Author	Specimen details	Viscosity [mPa·s]	Activation [mT]	Measured Characteristics	Experimental Rig	Load	Results
Li-Jun et al. 2009 [39]	Ferrofluid 20 nm 6 wt. %	N/A	0 – 80	Coefficient of friction (COF), Side leakage	Four-ball tester	392 N	Lower COF, reduced side leakage
Shen et al. 2009 [45]	Ferrofluid 15 nm 4.83 wt. %	67	0 – 10	COF	Pin on disc	20 N	Lower COF
Reyes et al. 2010 [50]	Ferrofluid 9 nm 5.5 wt. %	46 – 560	0 – 150	COF	Ball on disc	7 N	Reduced starvation
Song et al. 2013 [38]	MR Fluid 1 – 4 µm 32 wt. %	92 ± 15	0.5	COF, Wear rate	Pin on disc	20 – 100 N	Lower COF, wear rate reduction
Zhang et al. 2015 [41]	MR Fluid 72 – 86 wt. %	42 - 280	9	COF	Pin on disc	10 N	Higher COF

In the matter of magnetic fluids, a magnetic texture was created to improve the lubricant behaviour. The magnetic texture was manufactured using photolithography by filling the hollows with a magnetic film. At low sliding speed the magnetic texture causes “anti-friction” effect and keeps even more lubricant in comparison with simple texture. As the speed rises, the coefficient of friction value increases because of the higher yield stress.

3.3 Magnetic field effect on the lubricating layer thickness

The intensity variation of magnetic field applied on MR fluid causes changes in rheological properties, for instance, viscosity and load capacity [33,46]. Therefore, a considerable effort has been made to improve or replace commercial oils due to the requirements for a higher load capacity of mechanisms and trend of lowering the lubricant layer. Thereby, ferrofluids seem to be a suitable lubricating medium, because of their composition. The particle size of ferrofluids is relatively small, so there is much lower number of partial frictional contacts [47], however a change excited by external magnetic field can be achieved. The most important purpose is keeping the lubricant in contact area to prevent lubricant starvation and migration [39,48,49]. There was a study dealing with controlling of starvation in a ball-plate contact under sliding-rolling conditions using ferrofluid composed of 5.5 wt. % 9 nm particles. The contact area of the rotating aluminium disc and elastomer ball was excited by magnets underneath. The results show, that it is possible to reduce starvation using the magnetic field near the contact area [50].

The most important experimental studies of magnetic fluids are listed with parameters and achieved results in Table 1.

4. SMART FLUIDS INFLUENCED BY ELECTRICITY

Some of the smart fluids are sensitive to an external electric field stimulus, i.e. Electrorheological (ER) fluids [51]. ER fluid is a smart fluid that reacts to excitation of external electric field by creating chain structures between exciting poles as shown schematically at Fig. 4. This reaction changes the rheological properties of the ER fluid. The response time is generally around 10 ms and is strongly dependent on the particle size, magnitude of the excitation source and response of the entire system [52]. There are two types of ER fluids [53].

Positive - when there is an increase of yield stress and viscosity in the presence of an external electric field (e.g. polymers, fullerenes, liquid crystals, etc.) [53] and negative – when there is a decrease of yield stress and viscosity in the presence of external electric field (e.g. journal bearings, dampers etc.) [54,55]. Both, positive and negative

ER fluids can be used in applications [56–58], such as valves, dampers, journal bearings, microelectromechanical systems (MEMS), etc.

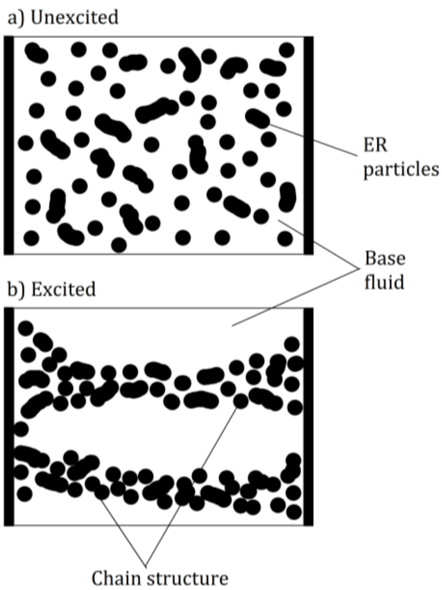

Fig. 4. Activation of ER fluid: (a) without electric field, (b) with electric field.

These fluids can be divided into three categories. Natural ER fluid – a fluid performing ER effect without additives (e.g. ionic liquids). Emulsion – a mixture of base oil and natural ER fluid (e.g. fatty alcohol in base oil) and suspension – made of polarizable particles dispersed in the base fluid.

Materials in liquid state, that can be excited by an external electric field without any additives are called natural ER fluids. An example of this category is ionic liquid – salts in liquid form with low melting points [59-61]. Ionic liquids are neutral to bright yellow transparent fluids containing organic or inorganic cations and anions. They also have relatively good chemical and thermal stability and they are non-flammable. The viscosity of ionic liquids varies from 20 to 200 mPa·s at 25 °C, according to the fluid composition. Another example for natural ER fluids are liquid crystals – organic liquids characterized by the “long-range” order of its molecular orientation [62,63]. The orientation changes according to concentration and temperature, respectively. Liquid crystals have been developed for displays of computers or television, however, there is a potential of application in tribomechanical systems as a smart fluid [60,64,65]. The main advantage of natural ER fluids is high sedimentation stability. On the other hand, the cost of mentioned liquids is relatively high [66].

When there is a need to make a natural ER fluid thinner, to adjust fluid properties or to combine two liquids with natural ER effect [66], an emulsion ER fluid is preferred. Such fluid is normally made of two liquid phases – base fluid (mostly oil or water) and a fluid that shows ER effect. There is good sedimentation stability in case of emulsion ER fluids, since there are no large particles present. For emulsion, a base fluid with good tribological behaviour can be used, normally mineral oils. Fluid with ER effect such as the liquid crystals, ionic liquids [66], acids (e.g. oleic or lauric) [67], paraffin, alcohol [68], etc. can be used. The concentration depends on the desired strength of ER effect and rheological properties [53].

Like the MR fluids, ER fluids can be also composited of base fluid, additives and a solid phase – in this case, dispersed polarizable particles. The base fluid can be made from isolating oil or another non-conductive fluid with high chemical stability. Most used base fluids are transformer, silicon, mineral or vegetable oils, kerosene, liquid paraffin etc. The base fluid should have a high boiling point (above 200 °C) and a viscosity below 10 Pa·s. The density of the base fluid should be above 1200 kg·m^{-3} for better sedimentation stability. High density oils as fluoro-silicon or fenyl-silicon oils are used because of lower sedimentation rate of dispersed particles. In the case of ER fluids, an important parameter of the base fluid is the breakdown strength, that should be higher than 7 kV·m^{-3} [53].

For better colloidal stability, various additives are used to improve the base fluid properties, such as ER effect response, sedimentation, tribological or other properties. Materials [53] that can be adsorbed on particle surface are surfactants, acids, alkaline soils, water, etc. Water is not suitable for certain applications, because at higher temperatures evaporation occurs, that may lead to loss of ER effect [69].

Particles in the ER fluids are chosen according to its specific physical characteristics, like conductivity and dielectric properties. The size of particles ranges from 0.1 to 100 μm [70]. Materials used for particle production [53] are ceramics, organic materials polymers, etc.

5. TRIBOLOGICAL BEHAVIOUR OF ER FLUIDS

Tribological performance and behaviour of ER fluids is very difficult to generalize, because of different character and composition. The main difference in lubrication, friction and wear mechanisms is the size of polarizable particles contained in the ER fluid. In the case of larger particles, there is a higher risk, that abrasive and erosive wear might occur. The damage caused by erosion is even more significant when an external electric field is applied, therefore besides the mechanical and chemical effect on contact surfaces, there is also electrical and electrochemical effect. As for the smaller particles, mostly likely another type of wear – adhesive wear will occur [71].

5.1 Tribological behaviour of non-activated ER fluids

There were several tribological experiments with the purpose to compare the non-activated ER fluids, especially suspensions, with the base fluid. Pin-on-disc tribometer was used to determine the effect of particles on contact surfaces. Adhesive wear dominant the ER fluid with 30 wt.% particles of size 12 microns made from polymethacrylate salt [71]. Although a decrease of frictional force was observed with ER fluid, extensive delamination of contact surface occurred. Similar results showed ER fluid made of silicon oil and phosphorated starch particles. In comparison with base oil, phosphorated starch-based ER fluid has stabilization effect on wear. However, there is a higher rate of material loss due to abrasive wear caused by dispersed particles [72]. Even though noticeable changes in tribological performance of ER particles in base fluid were observed, the excitation of external electric field might change the behaviour of an ER fluid significantly. For understanding the behaviour of ER fluids, it is necessary to include the external field excitation to the investigation process.

5.2 Tribological behaviour of activated ER fluids

Electric field can significantly change ER fluid properties and the tribological performance. The main problem with ER fluids is its relatively high demand for exciting voltage. According to the type of ER fluid, the needed external electric field intensity varies in range 1 to 1000 $MV \cdot m^{-1}$. Because most of the experiments were performed on a very small amount of fluid and in tiny gap, the external voltage could be laboratory supply up to 30 V. In case of ionic liquids [73], the used maximum voltage was only 10 V providing 1.02 $MV \cdot m^{-1}$. Such relatively small voltage induced a change in friction coefficient up to almost double of the initial value without the electric field. This effect was even more significant with higher load. The increase of friction coefficient was explained as the result of formation of the ordered anions and cations layers near the electrified interfaces, which caused the growth of effective viscosity. Similar increasing of friction coefficient at low speeds was also observed for emulsions with oleic acid and lauric acid [67]. In contrast with mentioned results, liquid crystals showed decreasing tendency with increasing voltage at speeds lower than 1 $mm \cdot s^{-1}$. This behaviour was reportedly caused by orientation of molecules in direction of electric field [74].

As well as the MR fluids, it is possible to apply ER fluid to the finishing operations of surfaces. Thanks to abrasive particles of ER fluid, a high quality of surfaces finishing can be achieved [75,76]. ER fluids were applied for finishing of K9 mirror surface reaching roughness Ra up to 2.5 nm [75]. Although, the increasing voltage in range of 1500 to 3000 V did not result in higher surface quality, the relative change of surface roughness was faster at a higher supply voltage. Therefore, supply voltage does not affect the surface quality, but still can speed up the finishing process.

5.3 Electric field influence on thickness of lubricating layer

The rheological properties of a fluid determine its lubrication performance especially the film thickness. In case of ER fluids, there is a possibility to change the fluid behaviour by electric field stimuli, thereby the lubricating layer. Since some of the ER fluids are transparent liquids, optical methods (such as optical interferometry) can be implemented for the film thickness evaluation. Furthermore, there is much lower risk of interaction of particles with contact surfaces thanks to the composition of some ER fluids that are made of tiny polarizable particles, such as the natural ER fluid. There were experiments carried out to examine the damping characteristics using liquid crystal as a lubricant in bearing pad [62].

The viscosity of liquid crystal increased with the increasing external voltage, however, noticeable changes were only observed in presence of relative high excitation voltage of 1500 V.

Because of the high requirement on supply power in bearing pad experimental rig and the high cost of liquid crystals, ionic liquids were applied. There was a possibility to use ball-on-disc tribometer based on optical interferometry for the lubricating layer evaluation. Because of the consistency of ionic liquids and their transparent appearance it was possible to apply an optical method for experiments. Observed ionic liquid was 1-butyl-3-methylimidazolium hexafluorophosphate ([BMIm]PF_6) [77]. During experiments the noticeable changes in film thickness even at relatively low voltage of 5 V (150 MV·m^{-1}) were observed. The change was more significant at a higher voltage of 10 V (300 MV·m^{-1}), which induced the growth of lubricating layer approximately by 16 nm as it is shown in Fig. 5. The change in lubricating layer was the result of increasing fluid viscosity caused by the structured ionic layer generation. Similar results were obtained in the study of an emulsion of n-decanol and n-heptane with different volume ratios in a point contact, where higher external voltages up to 30 V were applied [78]. The most significant change was observed at a ratio of 1:4 n-decanol to n-heptane, where an increase in film thickness reached around 8 nm. The effect of the external electric field on lubricating layer of ER fluid emulsions was confirmed by Luo [63], who applied oleic and lauric acid in base oil as a lubricant.

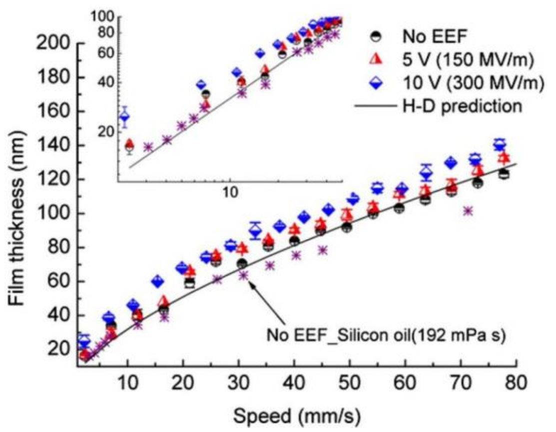

Fig. 5. Film thickness dependence on rolling speed in different electric field strength compared with Hammock-Dowson prediction (reprinted with permission from AIP Publishing) [77].

Even though electric field has a noticeable effect on the lubricating layer of ER fluids, there are some negative consequences in real mechanisms subjected to electric field, e.g. when electric charge passes through bearings etc. For that reasons, experiments were performed at “ball-on-disc” tribometer [79]. The results showed, that cavitation occurs, when the fluid – glycerine is subjected to electric field excitation. A similar study [80] was carried out to explain the influence of electric field on micro bubbles creation in liquid paraffin enriched by zinc dialkyl dithiophosphate (ZDDP) additive. However, the intensity of micro bubble creation increased slightly and only a little change in film thickness was achieved when subjected to electric field of external voltage 90 V. The effect of ZDDP in liquid paraffin on lubricating layer under electric field activation was explained as the ability of ZDDP molecules to reorder. Not only the voltage, but also polarity causes different mechanisms of wear [81]. Positive polarity is responsible for microbubble emergence and cavitation, while negative polarity results in severe surface damage caused by electro-chemical effect.

In another study, that dealt with the effects of negative electric field in mechanisms was focused on the lubricant starvation in ball bearings [82]. Capillary action secures the replenishment of lubricating layer. When the bearing is subjected to electric potential, lubricant micropool destabilization occurs and lubricant is being drawn out of the contact area. This phenomenon was examined on “ball-on-disc” tribometer using n-hexadecanol and paraffin oil. The results confirmed the effect of electric field on lubricant migration from the contact area, what may lead to surface damage caused by lubricant starvation as schematically compared at Fig. 6 with fully flooded conditions.

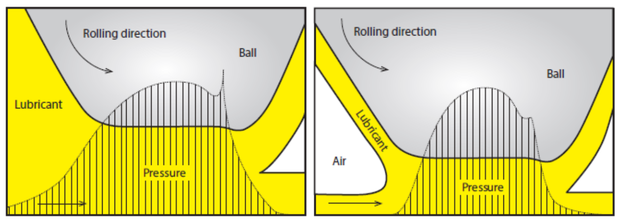

Fig. 6. Pressure profile (dotted line) and film thickness for fully flooded (left) and starved (right) EHL contact (reprinted with permission from ASME) [83].

Table 2. Summary of experiments – ER fluids

Author	Specimen details	Viscosity [mPa·s]	Activation [V]	Measured Characteristics	Experimental Rig	Load	Results
Xie et al. 2010 [80]	Liquid paraffin + 5 wt. % ZDDP	30.12	0 – 90	Lubricant film thickness (h_c)	Ball-on-disc tribometer	4 N (117 MPa)	Small increase of h_c
Xie et al. 2010 [77]	Ionic Liquids: [BMIm]PF_6 [HMIm]PF_6 [OMIm]PF_6	210 410 690	0 – 10	h_c	Ball-on-disc tribometer	0.53 GPa	Increase of h_c
Xie et al. 2011 [78]	Compound *n*-heptane / *n*-decanol	0.37 – 10.7	0 – 30	h_c	Ball-on-disc tribometer	28 N	Increase of h_c
Matsumura et al. 2012 [62]	Liquid crystal	28	0 – 1500	h_c, Apparent viscosity (η_{app})	Sliding pad with electrodes	4 N	Increase of h_c, increase of η_{app}
Kong et al. 2016 [73]	Ionic Liquids: [C_2MIM][BF_4] [C_4MIM][BF_4] [C_6MIM][BF_4]	41 98 300	0 - 10	COF	Reciprocating sliding tribometer	0,1 – 1 N (210 – 454 MPa	Almost double COF after excitation

Mathematical models provide a different way of ER fluid analysis to simplify design and confirm functionality. There were several studies dealing with thin lubricating films under external electric field, where optimization algorithm of steady-state ER fluids based on an extended Bingham model and reconfigurable electric field gradients control using FEM were introduced [84,85]. Some findings show, that the presence of electricity in lubricating layer causes a rise in film thickness during EHD regime, as well as an increase in apparent viscosity [86]. Another study that dealt with dynamic behaviour of negative ER fluid journal bearing provided mathematical analysis based on Reynolds equation. The results shown, that the negative ER fluid can significantly reduce damping with increasing electric field intensity (up to 3 kV/mm), when lower damping is required during the excitation speed [87]. For obtaining valuable results, the mathematical model should be verified with corresponding fluid as it is shown in an experimental study [88], where experiment results carried on a journal bearing filled with ER fluid shown a good agreement with the presented analysis – when the voltage was applied, the journal bearing became stiffer.

The most important experimental studies of ER fluids are listed with parameters and achieved results in Table 2.

6. FUTURE SCOPE

Smart fluids could be a new basis of high-efficient fully controllable smart mechanisms. Although ER fluid was already successfully applied in MEMS, there are numerous potential applications of smart fluids for improving performance and efficiency. Possibly, development of smart lubricants will allow production of smart bearings, where an external stimulus steadily changes the rheological properties of lubricant. Therefore, bearing load capacity can be easily increased as needed. It can also reduce the drag losses of an oil bath, when the lubricating film thickness is reduced after passing the initial starting phase resulting in higher efficiency and longer service life. There is also a high potential of using smart fluids, especially ionic liquids, for 100 % oxygen environments lubrication, such as compressors and pneumatic systems, where standard lubricants could not be used.

7. CONCLUSIONS

This paper reviewed two main classes of smart fluids, ER and MR, applicable in tribomechanical systems and the following concluding remarks were derived:

1. The performance of an MR fluid can be significantly improved with shape of ferromagnetic particles. Spherical particles are characteristic with quick response, while polymerized chains provide a higher yield stress under activation of external magnetic field.
2. To reduce sedimentation rate of MR fluids, bimodal suspensions made of particles with different size can be applied. Larger microparticles secure the strength of MR effect, while smaller nanoparticles provide higher stability and lower sedimentation rate of MR fluid.
3. The surface quality of contact surfaces in the contact area affects the lubricant performance. Application of magnetic texture with MR fluid provides a better lubrication stability and lubricant replenishment. In addition, at a lower speed, the "anti-friction" effect occurs because of the influence of the texture geometry and magnetic field on the particles.
4. Liquids and lubricants with natural ER effect are more suitable for thin film lubrication since there are tiny polarizable particles present that cause much smaller wear of contact surfaces.
5. The external voltage needed to induce changes in lubricating film is dependent on the size of gap between polarizable surfaces. Relatively high electric field intensity is required for ER fluids excitation (approx. 300 $MV\cdot m^{-1}$). In nanogap, a small external voltage (around 10 V) is enough to noticeably increase the film thickness, while a micron gap requires relatively high external voltage (up to 1500 V).
6. Since the price of smart fluids is relatively high, the mathematical models based on the experimental data of the fluid can be applied for CFD simulations. Therefore, development of new devices can be significantly improved.
7. The reviewed papers show, that magnetic fluids are more suitable for applications such as valves and dampers, etc., where a significant increase of effective viscosity is needed when the larger size of MR particles is not limiting the functionality, while the ER fluids (especially natural ER fluids, such as IL) can be used in smart bearings and mechanisms working in thin film lubrication regime.

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REFERENCES

[1] A. Chiolerio, M.B. Quadrelli, *Smart Fluid Systems: The Advent of Autonomous Liquid Robotics,* Advanced Science, vol. 4, no. 7, 2017, doi: 10.1002/advs.201700036

[2] S.B. Choi, N.M. Wereley, W. Li, M. Yu, J.H. Koo, *Applications of controllable smart fluids to mechanical systems*. Advances in Mechanical Engineering, vol. 2014, pp. 5–6, 2014, doi: 10.1155/2014/254864

[3] R. Stanway, *Smart fluids: current and future developments,* Materials Science and Technology, vol. 20, no. 8, pp. 931–939, 2004, doi: 10.1179/026708304225019867

[4] N.J. Balmforth, I.A. Frigaard, G. Ovarlez, *Yielding to Stress: Recent Developments in Viscoplastic Fluid Mechanics,* Annual Review of Fluid Mechanics, vol. 46, pp. 121-146, 2014, doi: 10.1146/annurev-fluid-010313-141424

[5] G. Bossis, S. Lacis, A. Meunier, O. Volkova, *Magnetorheological fluids,* Journal of Magnetism and Magnetic Materials, vol. 252, no. 1–3 SPEC. ISS., pp. 224–228, 2002, doi: 10.1016/S0304-8853(02)00680-7

[6] Z. Strecker, J. Roupec, I. Mazůrek, M. Klapka, *Limiting factors of the response time of the magnetorheological damper,* International Journal of Applied Electromagnetics and Mechanics, vol. 47, no. 2, pp. 541–550, 2015, doi: 10.3233/JAE-140006

[7] F.D. Goncalves, M. Ahmadian, J.D. Carlson, *Investigating the magnetorheological effect at high flow velocities,* Smart Materials and Structures, vol. 15, no. 1, pp. 75–85, 2006, doi: 10.1088/0964-1726/15/1/036

[8] B.J. Park, F.F. Fang, H.J. Choi, *Magnetorheology: materials and application,* Soft Matter, vol. 6, no. 21, pp. 5246-5353, 2010, doi: 10.1039/C0SM00014K

[9] W. Song, M.S. Seong, S.B. Choi, Ch. H. Lee, M. Cho, *Tribological characteristics of magneto-rheological fluid for movement sensor application,* Smart Materials and Structures, vol. 23, no. 1, 2014, doi: 10.1088/0964-1726/23/1/017001

[10] K. Karakoc, E.J. Park, A. Suleman, *Design considerations for an automotive magnetorheological brake,* Mechatronics, vol. 18, no. 8, pp. 434–447, 2008, doi: 10.1016/j.mechatronics.2008.02.003

[11] A. Grunwald, A.G. Olabi, *Design of magneto-rheological (MR) valve,* Sensors and Actuators, A: Physical, vol. 148, no. 1, pp. 211–223, 2008, doi: 10.1016/j.sna.2008.07.028

[12] Ş. Çeşmeci, T. Engin, *Modeling and testing of a field-controllable magnetorheological fluid damper,* International Journal of Mechanical Sciences, vol. 52, no. 8, pp. 1036–1046, 2010, doi: 10.1016/j.ijmecsci.2010.04.007

[13] J.D. Carlson, M.R. Jolly, *MR fluid, foam and elastomer devices,* Mechatronics, vol. 10, no. 4, pp. 555–569, 2000, doi: 10.1016/S0957-4158(99)00064-1

[14] M. Ashtiani, S.H. Hashemabadi, A. Ghaffari, *A review on the magnetorheological fluid preparation and stabilization,* Journal of Magnetism and Magnetic Materials, vol. 374, pp. 711–715, 2015, doi: 10.1016/j.jmmm.2014.09.020

[15] J. Gołdasz, B. Sapiński, *Insight into magnetorheological shock absorbers*, pp. 1–224, 2015, doi: 10.1007/978-3-319-13233-4

[16] J.P. Rich, P.S. Doyle, G.H. Mckinley, *Magnetorheology in an aging, yield stress matrix fluid,* Rheologica Acta, vol. 51, no. 7, pp. 579–593, 2012, doi: 10.1007/s00397-012-0632-z

[17] S. Genc, P.P. Phule, *Rheological properties of magnetorheological fluids*, Smart Materials & Structures, vol. 11, no. 1, pp. 140–146, 2002, doi: 10.1088/0964-1726/11/1/316

[18] K. Raj, B. Moskowitz, R. Casciari, *Advances in ferrofluid technology,* Journal of Magnetism and Magnetic Materials, vol. 149, no. 1–2, pp. 174–180, 1995, doi: 10.1016/0304-8853(95)00365-7

[19] K. Raj, R.J. Boulton, *Ferrofluids - Properties and applications,* Materials and Design, vol. 8, no. 4, pp. 233–236, 1987, doi: 10.1016/0261-3069(87)90139-7

[20] E. Svåsand, K. De L. Kristiansen, Ø. G. Martinsen, G. Helgesen, S. Grimnes, A. T. Skjeltorp, *Behavior of carbon cone particle dispersions in electric and magnetic fields,* Colloids and Surfaces A: Physicochemical and Engineering Aspects, vol. 339, no. 1–3, pp. 211–216, 2009, doi: 10.1016/j.colsurfa.2009.02.025

[21] N. Jahan, S. Pathak, K. Jain, R.P. Pant, *Enchancment in viscoelastic properties of flake-shaped iron based magnetorheological fluid using ferrofluid*, Colloids and Surfaces A: Physicochemical and Engineering Aspects, vol. 529, no. March, pp. 88–94, 2017, doi: 10.1016/j.colsurfa.2017.05.057

[22] P. Kuzhir, M.T. López-López, G. Vertelov, Ch. Pradille, G. Bossis, *Shear and squeeze rheometry of suspensions of magnetic polymerized chains,* Rheologica Acta, vol. 47, no. 2, pp. 179–187, 2008, doi: 10.1007/s00397-007-0230-7

[23] J.L. Viota, F. González-Caballero, J.D.G. Durán, A. V. Delgado, *Study of the colloidal stability of concentrated bimodal magnetic fluids,* Journal of Colloid and Interface Science, vol. 309, no. 1, pp. 135–139, 2007, doi: 10.1016/j.jcis.2007.01.066

[24] J. De Vicente, D.J. Klingenberg, R. Hidalgo-Alvarez, *Magnetorheological fluids: a review,* Soft Matter, vol. 7, no. 8, pp. 3701-3710, 2011, doi: 10.1039/C0SM01221A

[25] I.A. Brigadnov, A. Dorfmann, *Mathematical modelling of magnetorheological fluids,* Continuum Mech. Thermodyn., vol. 17, no. 1, pp. 29–42, 2005, doi: 10.1007/s00161-004-0185-1

[26] D. Susan-Resiga, *A rheological model for magneto-rheological fluids,* Journal of Intelligent Material Systems and Structures, vol. 20, no. 8, pp. 1001–1010, 2009, doi: 10.1177/1045389X08100979

[27] D.A. Bompos, P.G. Nikolakopoulos, *Simulation Modelling Practice and Theory CFD simulation of magnetorheological fluid journal bearings,* Simulation Modelling Practice and Theory, vol. 19, no. 4, pp. 1035-1060, 2011, doi: 10.1016/j.simpat.2011.01.001

[28] M.I. Varela-Jiménez, J.L. Vargas Luna, J.A. Cortés-Ramírez, G. Song, *Constitutive model for shear yield stress of magnetorheological fluid based on the concept of state transition,* Smart Materials and Structures, vol. 24, no. 4, 2015, doi: 10.1088/0964-1726/24/4/045039

[29] P.L. Wong, W.A. Bullough, C. Feng, S. Lingard, *Tribological performance of a magneto-rheological suspension,* Wear, vol. 247, no. 1, pp. 33–40, 2001, doi: 10.1016/S0043-1648(00)00507-X

[30] K. Shahrivar, A.L. Ortiz, J. De Vicente, *A comparative study of the tribological performance of ferrofluids and magnetorheological fluids within steel-steel point contacts,* Tribology International, vol. 78, pp. 125–133, 2014, doi: 10.1016/j.triboint.2014.05.008

[31] J.W. Sohn, S.B. Choi, Ch.H. Lee, M.W. Cho, *Wear Characteristics of Magnetorheological Fluid under Boundary Lubrication,* Advanced Materials Research, vol. 79–82, pp. 83–86, 2009, doi: 10.4028/www.scientific.net/AMR.79-82.83

[32] A. Bombard, F.R. Goncalves, K. Shahrivar, A.L. Ortiz, J. De Vicente, *Tribological behavior of ionic liquid-based magnetorheological fluids in steel and polymeric point contacts,* Tribology International, vol. 81, pp. 309–320, 2014, doi: 10.1016/j.triboint.2014.09.013

[33] E. Uhlmann, G. Spur, N. Bayat, R. Patzwald, *Application of magnetic fluids in tribotechnical systems,* Journal of Magnetism and Magnetic Materials, vol. 252, no. 1–3 SPEC. ISS., pp. 336–340, 2002, doi: 10.1016/S0304-8853(02)00724-2

[34] D.J. Klingenberg, *Magnetorheology: Applications and challenges,* AIChE Journal, vol. 47, no. 2, pp. 246–249, 2001, doi: 10.1002/aic.690470202

[35] J. Seok, S.O. Lee, K.I. Jang, B.K. Min, S.J. Lee, *Tribological properties of a magnetorheological (MR) fluid in a finishing process,* Tribology Transactions, vol. 52, no. 4, pp. 460–469, 2009, doi: 10.1080/10402000802687932

[36] P. Zhang, K.H. Lee, Ch.H. Lee, *Reciprocating friction characteristics of magneto-rheological fluid for aluminum under magnetic field,* Transactions of Nonferrous Metals Society of China (English Edition), vol. 24, no. 1, pp. 171–176, 2014, doi: 10.1016/S1003-6326(14)63044-2

[37] H.W. Sun, S.C. Yang, *Revolved Surface Finishing with Smart Fluid Abrasives,* Key Engineering Materials, vol. 304–305, pp. 579–583, 2006, doi: 10.4028/www.scientific.net/KEM.304-30.579

[38] W.L. Song, Ch.H. Lee, S. B. Choi, *Sliding wear behavior of magnetorheological fluid for brass with and without magnetic field,* Transactions of Nonferrous Metals Society of China (English Edition), vol. 23, no. 2, pp. 400–405, 2013, doi: 10.1016/S1003-6326(13)62476-0

[39] W. Li-Jun, G. Chu-Wen, Y. Ryuichiro, W. Yue, *Tribological properties of Mn-Zn-Fe magnetic fluids under magnetic field,* Tribology International, vol. 42, no. 6, pp. 792–797, 2009, doi: 10.1016/j.triboint.2008.10.009

[40] W.L. Song, S.B. Choi, J.Y. Choi, Ch. H. Lee, *Wear and Friction Characteristics of Magnetorheological Fluid under Magnetic Field Activation,* Tribology Transactions, vol. 54, no. 4, pp. 616–624, 2011, doi: 10.1080/10402004.2011.584365

[41] P. Zhang, K.H. Lee, C.H. Lee, *Friction behavior of magnetorheological fluids with different material types and magnetic field strength,* Chinese Journal of Mechanical Engineering, vol. 29, no. 1, pp. 84–90, 2016, doi: 10.3901/CJME.2015.1126.139

[42] Z.D. Hu, H. Yan, H.Z. Qiu, P. Zhang, Q. Liu, *Friction and wear of magnetorheological fluid under magnetic field,* Wear, vol. 278–279, pp. 48–52, 2012, doi: 10.1016/j.wear.2012.01.006

[43] P. Zhang, K.H. Lee, C.H. Lee, *Fretting friction and wear characteristics of magnetorheological fluid under different magnetic field strengths,* Journal of Magnetism and Magnetic Materials, vol. 421, pp. 13–18, 2017, doi: 10.1016/j.jmmm.2016.07.064

[44] K. Shahrivar, J. De Vicente, *Ferrofluid lubrication of compliant polymeric contacts: Effect of non-homogeneous magnetic fields,* Tribology Letters, vol. 56, no. 2, pp. 281–292, 2014, doi: 10.1007/s11249-014-0408-y

[45] C. Shen, W. Huang, G. Ma, X. Wang, *A novel surface texture for magnetic fluid lubrication*, Surface and Coatings Technology, vol. 204, no. 4, pp. 433–439, 2009, doi: 10.1016/j.surfcoat.2009.08.003

[46] N. Vaz, K. G. Binu, P. Serrao, M.P. Hemanth, J. Jacob, N. Roy, E. Dias, *Experimental Investigation of Frictional Force in a Hydrodynamic Journal Bearing Lubricated with Magnetorheological Fluid,* Journal of Mechanical Engineering and Automation, vol. 7, no. 5, pp. 131–134, 2017, doi: 10.5923/j.jmea.20170705.01

[47] W. Huang, X. Wang, *Ferrofluids lubrication: a status report,* Lubrication Science, vol. 28, no. 1, pp. 3–26, 2016, doi: 10.1002/ls.1291

[48] H. Ke, W. Huang, X. Wang, *Controlling lubricant migration using ferrofluids,* Tribology International, vol. 93, pp. 318–323, 2016, doi: 10.1016/j.triboint.2015.09.038

[49] R.S. Anand, P. Kumar, *Effect of Starvation on Elastohydrodynamically Lubricated Contacts using Magnetorheological Fluids*, in RAM-2015 Conference, 15-17 May, 2015, SVNIT SuratAt: Surat, Gujarat, India, pp. 1–6.

[50] E.A. Reyes, J. De Vincente, R. Hidalgo-Álvarez, C. Myant, T. Reddyhoff, H.A. Spikes, *Soft elasto-hydrodynamic lubrication,* Tribology Letters, vol. 39, no. 1, pp. 109–114, 2010, doi: 10.1007/s11249-010-9623-3

[51] T.C. Halsey, J.E. Martin, D. Adolf, *Rheology of electrorheological fluids,* Physical Review Letters, vol. 68, no. 10, pp. 1519–1522, 1992, doi: 10.1103/PhysRevLett.68.1519

[52] J.C. Hill, T.H. Van Steenkiste, *Response times of electrorheological fluids,* Journal of Applied Physics, vol. 70, pp. 1207-1211, 1991, doi: 10.1063/1.349574

[53] T. Hao, *Electrorheological fluids,* Advanced Materials, 2001, vol. 13, no. 24, pp. 1847–1857, 2001, doi: 10.1002/1521-4095(200112)13:24<1847::AID-ADMA1847>3.0.CO;2-A

[54] C. Boissy, P. Atten, J.N. Foulc, *On a negative electrorheological effect,* Journal of Electrostatics, vol. 35, no. 1, pp. 13–20, 1995, doi: 10.1016/0304-3886(95)00015-3

[55] Y.G. Ko, U.S. Choi, *Negative electrorheological fluids*. Journal of Rheology, vol. 57, no. 6 (1655), 2013, doi: 10.1122/1.4821857

[56] K. Yoshida, N. Tsukamoto, J.W. Kim, S. Yokota, *A study on a soft microgripper using MEMS-based divided electrode type flexible electro-rheological valves*, Mechatronics, vol. 29, pp. 103–109, 2015, doi: 10.1016/j.mechatronics.2014.07.007

[57] P. Abgrall, N.T. Nguyen, *Nanofluidic devices and their applications*. Analytical Chemistry, vol. 80, no. 7, pp. 2326–2341, 2008, doi: 10.1021/ac702296u

[58] U.S. Choi, Y.S. Park, S.S. Lee, *Electrorheological behavior of chitosan succinate suspension as an anhydrous ER fluid*. Colloids and Surfaces A: Physicochemical and Engineering Aspects, vol. 211, no. 1, pp. 85–90, 2002, doi: 10.1016/S0927-7757(02)00234-0

[59] J. Dupont, R.F. De Souza, P.A.Z. Suarez, *Ionic liquid (molten salt) phase organometallic catalysis,* Chemical Reviews, vol. 102, no. 10, pp. 3667–3692, 2002, doi: 10.1021/cr010338r

[60] M.D. Bermúdez, A.E. Jiménez, J. Sanes, F.J. Carrión, *Ionic liquids as advanced lubricant fluids*, Molecules, vol. 14, no. 8, pp. 2888–2908, 2009, doi: 10.3390/molecules14082888

[61] Z. Lei, B. Chen, Y.M. Koo, D.R. Macfarlane, *Introduction: Ionic Liquids*. Chemical Reviews, vol. 117, no. 10, pp. 6633–6635, 2017, doi: 10.1021/acs.chemrev.7b00246

[62] Y. Matsumura, T. Shiraishi, S. Morishita, *Stiffness and damping of liquid crystal lubricating film under electric field,* Tribology International, vol. 54, pp. 32–37, 2012, doi: 10.1016/j.triboint.2012.05.009

[63] M. Gao, L. Ma, J. Luo, *Effect of Alkyl Chain Length on the Orientational Behavior of Liquid Crystals Nano-Film,* Tribology Letters, vol. 62, no. 2, pp. 1–7, 2016, doi: 10.1007/s11249-016-0663-1

[64] C.J. Reeves, A. Siddaiah, P.L. Menezes, *Tribological study of imidazolium and phosphonium ionic liquid-based lubricants as additives in carboxylic acid-based natural oil: Advancements in environmentally friendly lubricants,* Journal of Cleaner Production, vol. 176, pp. 241–250, 2018, doi: 10.1016/j.jclepro.2017.12.099

[65] I. Minami, *Ionic liquids in tribology,* Molecules (Basel, Switzerland), vol. 14, no. 6, pp. 2286–2305, 2009, doi: 10.3390/molecules14062286

[66] Y. Zhou, J. Qu, *Ionic liquids as lubricant additives: A review,* ACS Applied Materials and Interfaces, vol. 9, no. 4, pp. 3209–3222, 2017, doi: 10.1021/acsami.6b12489

[67] J.B. Luo, M.W. Shen, S.Z. Wen, *Tribological properties of nanoliquid film under an external electric field,* Journal of Applied Physics, vol. 96, no. 11, pp. 6733–6738, 2004, doi: 10.1063/1.1806259

[68] G. Xie, J. Luo, S. Liu, D. Guo, Ch. Zhang, *Thin liquid film lubrication under external electrical fields: Roles of liquid intermolecular interactions,* Journal of Applied Physics, vol. 109, no. 11, 2011, doi: 10.1063/1.3587477

[69] T.C. Halsey, *Electrorheological Fluids,* Science (New York, N.Y.). 1992, vol. 258, no. 5083, pp. 761–766, 1992, doi: 10.1126/science.258.5083.761

[70] P. Dong, Ch. Wang, S. Zhao, *Preparation of high performance electrorheological fluids with coke-like particles from FCC slurry conversion*. Fuel, vol. 84, no. 6 SPEC. ISS., pp. 685–689, 2005, doi: 10.1016/j.fuel.2004.03.021

[71] S. Lingard, W.A. Bullough, W.M. Shek, *Tribological performance of an electro-rheological fluid*, Journal of Physics D: Applied Physics, vol. 22, pp. 1639–1645, 1989, doi: 10.1088/0022-3727/22/11/012

[72] S.B. Choi, J.W. Sohn, Y.M. Han, Ch.H. Lee, *Wear Characteristics Under Boundary Lubrication Contacts in Phosphorated Starch-Based Electrorheological Fluid,* Tribology Transactions, vol. 53, no. 2, pp. 256–265, 2010, doi: 10.1080/10402000903312331

[73] L. Kong, W. Huang, X. Wang, *Ionic liquid lubrication at electrified interfaces,* Journal of Physics D: Applied Physics, vol. 49, no. 22, 2016, doi: 10.1088/0022-3727/49/22/225301

[74] Y. Gao, B. Xue, L. Ma, J. Luo, *Effect of liquid crystal molecular orientation controlled by an electric field on friction,* Tribology International, vol. 115, no. June, pp. 477–482, 2017, doi: 10.1016/j.triboint.2017.06.021

[75] H. Cheng, J. Su, Y. Chen, H.Y. Tam, *Profile and roughness of electrorheological finishing optical*

surfaces, Frontiers of Optoelectronics, vol. 8, no. 3, pp. 306–313, 2015, doi: 10.1007/s12200-014-0401-y

[76] J. Su, H. Cheng, Y. Wen, Y. Feng, H.Y. Tam, *Investigation into the mechanism for ultra smooth electrorheological finishing using wheel-like finishing tool,* Journal of Materials Processing Technology, vol. 238, pp. 124–131, 2016, doi: 10.1016/j.jmatprotec.2016.07.019

[77] G. Xie, J. Luo, D. Guo, S. Liu, *Nanoconfined ionic liquids under electric fields*, Applied Physics Letters, vol. 96, no. 4, pp. 1-3, 2010, doi: 10.1063/1.3292213

[78] G. Xie, J. Luo, S. Liu, D. Guo, Ch. Zhang, *Nanoconfined liquid aliphatic compounds under external electric fields: roles of headgroup and alkyl chain length,* Soft Matter, vol. 7, no. 9, pp. 4453-4460, 2011, doi: 10.1039/C0SM00971G

[79] Y. He, J. Luo, G. Xie. *Characteristics of thin liquid film under an external electric field*. Tribology International, vol. 40, no. 10-12 SPEC. ISS., pp. 1718–1723, 2007, doi: 10.1016/j.triboint.2007.02.007

[80] G. Xie, G. Li, J.B. Luo, S.H. Liu, *Effects of electric field on characteristics of nano-confined lubricant films with ZDDP additive*, Tribology International, vol. 43, no. 5–6, pp. 975–980, 2010, doi: 10.1016/j.triboint.2009.12.067

[81] G. Xie, L. Si, D. Guo, S. Liu, J. Luo, *Interface characteristics of thin liquid films in a charged lubricated contact*, Surface and Interface Analysis, vol. 47, no. 3, pp. 315–324, 2015, doi: 10.1002/sia.5710

[82] G. Xie, Z. Cui, L. Si, D. Guo. *Destabilization of lubrication oil micropool under charged conditions,* Industrial Lubrication and Tribology, vol. 69, no. 1, pp. 59–64, 2017, doi: 10.1108/ILT-11-2015-0184

[83] D. Kostal, P. Sperka, P. Svoboda, I. Krupka, M. Hartl, *Influence of Lubricant Inlet Film Thickness on Elastohydrodynamically Lubricated Contact Starvation*, Journal of Tribology, vol. 139 no. 5, pp. 1-6, 2017, doi: 10.1115/1.4035777

[84] J.C. De Los Reyes, I. Yousept, *Optimal control of electrorheological fluids through the action of electric fields*, Computational Optimization and Applications, vol. 62, no. 1, pp. 241–270, 2015, doi: 10.1007/s10589-014-9705-5

[85] S. Boedo, *Formation of dynamic reconfigurable electric field gradients in thin lubricant films through transient elastohydrodynamic squeeze film action*, Tribology International, vol. 116, no. June, pp. 329–337, 2017, doi: 10.1016/j.triboint.2017.07.013

[86] Q. Zuo, P. Huang, F. Su, *Theory analysis of asymmetrical electric double layer effects on thin film lubrication*, Tribology International, vol. 49, pp. 67–74, 2012, doi: 10.1016/j.triboint.2011.12.021

[87] A. Bouzidane, M. Thomas, *An electrorheological hydrostatic journal bearing for controlling rotor vibration*, Computers and Structures, vol. 86, pp. 463-472, 2008, doi: 10.1016/j.compstruc.2007.02.006

[88] P.G. Nikolakopoulos, C.A. Papadopoulos, *Controllable high speed journal bearings, lubricated with electro- rheological fluids*, *An analytical and experimental approach.* Tribology International, vol. 31, no. 5, pp. 225-234, 1998, doi: 10.1016/S0301-679X(98)00025-5