Comparison between Synthetic Oil Lubricants for Reducing Fretting Degradation in Lightly Loaded Gold-Plated Contacts

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Abstract

This paper presents a comparison between the performances of two chemistries of synthetic oil lubricants, polyalphaolefins (PAOs) and perfluoropolyethers (PFPEs) when applied on gold-plated electrical contacts operating at contact loads of 9.8 cN and experiencing fretting-induced degradation. Performance assessment was done using the contact resistance and coefficient of friction behavior and the surface's response to fretting in the presence of different types of lubricants within the two chemistries. It was found that the PAOs improved the fretting performance of the lightly loaded contacts, and statistically, were at least fifty times more reliable for a longer duration of fretting cycles than the PFPEs, suggesting their suitability for low contact load applications. At low loads, PFPEs underwent contact separation due to hydrodynamic lubrication, and the behavior was more observable among the PFPEs having higher kinematic viscosities. On the contrary, viscous PAOs had improved fretting performance and delayed time to contact failure than less viscous PAOs. The applied lubricant film thickness also contributed to the contact's performance, and it was found that increasing the thickness of the PFPE films advanced contact failures, while the PAO film postponed contact's time to failure.

1 Introduction

Electrical contacts are integral components in all connectors and switches. Gold is the preferred plating material for contacts in high-reliability, low-power applications such as connectors or switches inside electronic devices used in the medical or data communications industries. Gold, being a noble metal, is resistant to oxidation and has excellent electrical properties. Gold-plated contacts deliver low and stable electrical contact resistance (ECR), usually around a few milliohms when they are new and healthy. However, these contacts are susceptible to wear in the presence of fretting or when they mate and demate. Fretting wear is a common failure mechanism in contacts used in radio frequency (RF) and microwave switches, which have an expected life of at least one million switching cycles. The contacting surfaces experience repetitive relative micromotions during operation, resulting in fretting wear and exposing the oxidizable layers underneath the gold plating when the gold has worn away.

Lubricating electrical contacts using various lubricants are an economical way to reduce fretting wear and possible corrosion. Synthetic oil-based organic lubricants, such as perfluoropolyethers (PFPEs), a class of halogen-containing fluids, have previously been found to reduce fretting wear in gold-plated electrical contacts [1]–[8]. However, studies concerning the wear on contacts were performed at contact loads where the normal force operating between the contacting surfaces was at least 50 centiNewtons (cN). Generally, the gold-plated contacts operate at loads higher than 100 cN, but applications are emerging that require contacts to operate at contact loads around a few centiNewtons or even lower. Holm [9] distinguished contacts operating at loads lower than 20 cN as microcontacts, referred to in this study as lightly loaded or low-load contacts. For example, contacts in many RF and microwave switches are designed to operate at contact loads of around 10 cN, whereas contacts in micro-electro-mechanical system (MEMS) switches are designed to operate at contact loads of around a thousandth of a centiNewton. While dry or unlubricated gold-plated contacts can deliver low and stable ECR for a few thousand fretting cycles even at such low loads, the presence of organic lubricants between the contacting surfaces can also raise ECR and reduce electrical contact performance. This is because these lubricants are insulating materials with volume resistivity in the range of 10^5–10^{13} Ω×m, which is 12–20 orders of magnitude higher than the resistivity of commercial metals [10].

Studies [11]–[13] have shown that some lubricated contacts under stationary conditions—where no relative motion between the contacts is observed—had higher ECR than unlubricated contact cases and that the lubricants can reduce or even prevent asperity contact between the surfaces at low contact loads. Depending upon the type and chemistry of lubricant used, the effect of increased ECR was even seen at contact loads as low as 0.2 cN and as high as 20 cN for oil-based lubricants. The lubricant's characteristics—its type (oil or grease), chemistry, rheology, viscosity, and the applied lubricant film thickness—determines the effect on ECR at contact loads where an increase is noticeable. Similarly, Tamai et al. [14] found that olefin-lubricated contacts showed higher ECR than unlubricated contacts at contact loads below 3.92 cN (4 gf). For conventional electrical contact applications where the contact loads are at least 1 N, the lubricant film does not cause any adverse effect on the ECR because the contact load is high enough to squeeze the applied lubricant into the gaps between asperities, often allowing sufficient metal asperities to mate and establish low and stable ECR. Hence, at high contact loads, the lubricated and unlubricated contacts display nearly the same ECR values. However, the problem arises when the contact load or the applied normal force is not strong enough to overcome the film strength to establish stable ECR. This warrants a reevaluation of the guidelines for selecting a lubricant, and the lubricants that have proven beneficial for high contact loads must be assessed carefully for lightly loaded contact applications.

Selecting a lubricant is challenging not only for lightly loaded contact applications but also for conventional electrical contact applications. Not all lubricants can improve the contact's performance and useful functional life; thus, a lubricant should be chosen carefully as per the application requirement and involving factors such as the contact load, contact materials and geometry, environment, and more. Antler [1][2] found that PFPE-based lubricants performed better than other classes, such as polyalphaolefins (PAOs), hydrocarbons, and silicon-containing fluids for gold-plated contacts subjected to fretting conditions. PFPE- and PAO-based synthetic lubricants are commonly available owing to their successful and widespread use with electrical contacts. PFPE-based lubricants are generally preferred for gold-plated contacts over other classes because the fluorine atoms in the lubricant molecules can bond with the gold atoms and provide adequate boundary lubrication. However, this preference for PFPEs comes from a limited number of studies performed under high contact load conditions, while their performance under low contact load conditions is not well understood.

Hence, this study aims to assess and compare the fretting performance of contacts each lubricated with PFPE- and PAO-based synthetic oil lubricants and operating at low loads (also referred to as lightly loaded conditions in this paper) of 9.8 cN (10 gf). The effects of fretting on dry/unlubricated contacts are also discussed for reference and used for comparison with lubricated contacts. Additionally, the study shows how the lubricant's viscosity and the applied film thickness affect contact's behavior in terms of

ECR, the expected cycles to enter a particular wear region (the different wear regions discussed later in the experimental section), onset of lubrication behavior, and contact failure.

2 Experimental Method

This section describes the test setup and methodology used for conducting the fretting tests. Additionally, it details the geometry and material composition of the contacts used, the lubricants tested, and the process of applying the lubricants on one of the contacts, namely the flats. This section also discusses the testing data obtained in this study and the analytical techniques used.

A contact resistance measurement probe (CRP) setup was used to imitate a controlled fretting motion at a set frequency and contact load between the contact pair, namely the pin and the flat, and to acquire ECR and friction force during the test. The CRP setup consisted of a table translating vertically over a spacer using a two-phase stepper motor to control its vertical motion. A holding fixture that mounts the pin was attached to the bottom of the table, as shown in Fig. 1. Similarly, the flat was placed over the piezo actuator and fixed tightly at its location using screws. The normal force between the contact pair, the pin, and the flat was controlled using the stepper motor's vertical motion, which pushed the pin toward the flat and set it at a desired normal load. Two load cells were used to measure the loads: one for the normal force and the other for the friction force. The normal force, which was measured as a reaction to the pin when it touched the flat (contact load), could be as high as 588 cN (~600 gf) and was controlled with an accuracy of 0.29 cN (0.3 gf). A second load cell in the holding fixture placed orthogonally to the normal force-measuring load cell measured the friction force experienced by the pin during fretting, and both the load cells were used to calculate the coefficient of friction (COF) indirectly. An Agilent 34401A digital multimeter (DMM) was connected to the contact pair for measuring the ECR, and measurements were made using the four-wire resistance method. For imparting the fretting motion, the bolted flat over the piezo actuator provided a sinusoidal wave motion up to an amplitude of 100 μm with a frequency going up to 65 Hz. A LabVIEW program was used for measuring and controlling the parameters as mentioned above.

Before the fretting test, a stationary test measuring the ECR with unit load increments from 0 to 50 cN (51 gf) was conducted to obtain the normal load, after which the changes in ECR became minimal. The contact pair—pin and flat—was made to establish contact under a normal load of 9.8 cN (10 gf) set at the beginning of the fretting test; however, the contact load was also controlled at defined intervals of cycles during fretting for consistency in results. The piezo actuator induced a sinusoidal fretting wave motion on the flat characterized by a fretting displacement of 80 μm at a frequency of 50 Hz. The test was run until one of two criteria were met (i.e., until either ECR reached 10 Ω five times in total during the test or the completion of 15 million cycles, whichever condition occurred first). For measuring the friction force, and thus COF, the test was interrupted at fixed intervals of cycles (as mentioned in Table 1 below) to conduct measurements of test parameters for one complete cycle at a frequency of 0.5 Hz. The test was interrupted at 0.5 Hz to acquire ECR, friction, and normal force measurements across multiple points on the wear track, which was not possible with the high frequency of 50 Hz. The results section of this paper presents the ECR and coefficient of friction (COF) data versus fretting cycles, and the COF was calculated using the friction force and normal load measured during the fretting motion. All tests were conducted at room temperature.

Table 1 Duration of interval for measuring test parameters at 0.5 Hz during the fretting test

Total Cycles Completed	*Duration of Interval (Cycles)*
< 1000	100
1,001–10,000	1,000
10,001–100,000	10,000
> 100, 000	100, 000

The contact specimens used were (1) a hemispherical-shaped pin with a diameter of 1.033 mm and a central dimple or depression of 0.067 mm and (2) a 4 cm × 4 cm flat of 0.355 mm thickness. Both the pin and the flat were plated with a protective layer of gold, with the pin having 2.2 μm of Au / 2.5 μm electroless Ni underplate / BeCu alloy-base metal. The flat was plated with 1 μm of Au / 1 μm Pd-Ni underplate / BeCu alloy-base metal, and the Pd-Ni underplate used was 20% Ni and 80% Pd. The average surface roughness, R_a, on the flats was 0.1 μm. The different plating designs of the pin and the flat were adopted to match the contact design specifications used in certain commercial and industrial products (not listed here to maintain the confidentiality of both the product and the project sponsor). The rationale for using a thicker protective gold layer over a thick nickel underplate on the pin as opposed to the flat was that the pin experienced a higher rate of wear than the flat during field conditions. For the fretting tests, separate individual pins were used for conducting different tests, while multiple locations on the same flat were used for a given lubricated case.

Three types of each of PFPE- and PAO-based synthetic lubricant were applied on the flats, and the pin and lubricated flats were used as test samples. Table 2 shows the lubricants and their relevant chemistry. The lubricants were selected following an assessment of the actual product's operating field condition and requirements and the desired lubricant properties. The contact pair—pin and flat—was used for each lubricant. A dry or unlubricated contact was also used for comparison.

Prior to testing, the contact pair was cleaned. The cleaning process for flats involved ultrasonic cleaning for 5 minutes in 1% alkaline solution, 5 minutes in acetone, and 5 minutes in 99% isopropyl alcohol. The pins were cleaned in an ultrasonic bath of 99% isopropyl alcohol only. Both the flats and the pins were then allowed to dry for one day in a closed petri dish. The cleaning process for the pins and the flats was different because the latter was cut from a larger-sized plate of 12 cm × 8 cm, so in addition to dust and external contaminants, the flats also had metal chips accumulated over their surfaces. Post-cleaning, the lubricant was applied on the flats only using a spin coating procedure. Once a flat was on the spin coater and covered with a layer of lubricant, it was rotated at 6,000 rpm for 2 minutes to let a consistent and thin lubricant film settle over its surface, while centrifugal forces from the spin coater removed the excess lubricant. The flat was then allowed to dry for 24 hours so the solvent in the solvent-dissolved lubricants could evaporate, namely the x % solutions in Table 2. This method deposited a thin lubricant film that was measured using the J.A. Woolam M-2000 Ellipsometer; these measured thicknesses of the various lubricant films are listed in Table 2.

Table 2 Lubricant samples used in the study

Base Oil Type	Lubricant Name	Name used in the study	Type (Applied as)	Kinematic Viscosity at 40°C (cSt)	Thickness (nm)
PFPE	Electrolube DOF	PFPE–A	Oil (1% solution)	280†	45 ± 3
PFPE	Kluberalpha KRA3-730 LV	PFPE–B	Oil (2% solution)	156	332 ± 48
PFPE	Demnum S-200	PFPE–C (2%)	Oil (2% solution)	200	51 ± 9
PFPE	Demnum S-200	PFPE–C (100%)	Oil (neat)	200	1615 ± 379
PAO	Nye 181	PAO–A	Oil (neat)	49.9	1266 ± 110
PAO	Nye 315A	PAO–B	Oil (neat)	28.5	831 ± 58
PAO	Nye 533J2	PAO–B (2%)	Oil (2% solution)	28.5	25 ± 2
-	Unlubricated	Unlubricated	-	-	-

† *Viscosity at 20°C*

Both optical microscopy and scanning electron microscopy (SEM) were used to identify the wear pattern, material buildup, and any significant surface behavior after the fretting test was complete. Energy-dispersive X-ray spectroscopy (EDS) analysis was used to identify the elements present in the contact zone. An FEI Quanta 200 was used for SEM and EDS with 25 kV of accelerating voltage and spot size of 3 to achieve higher spatial resolution during the analysis. A reference EDS point analysis was also conducted on both unlubricated and lubricated flats and unlubricated pins.

3 Experimental Results

This section details the different behaviors of the contact resistance for both the dry or unlubricated and PFPE- and PAO- lubricated contacts at the set test conditions, and mechanisms responsible for the test failures per contact case. COF experienced by the contacts during the micromotions, and their surface conditions, i.e., the surface degradation resulting from the fretting mechanisms are used to assess the effects of lubricants. Additionally, the influence of factors such as the lubricant's chemistry, kinematic viscosity, and applied lubricant film thickness on the contact's fretting performance are also discussed.

3.1 Effect of Lubricant Chemistry

3.1.1 Unlubricated Contact

Unlubricated contacts generally met the test end criteria prior to a million fretting cycles, with one test ending at a maximum of 1.67 million cycles. All the tests demonstrated a similar trend of ECR and COF. Fig. 2 shows the variation in ECR and COF experienced in the test ending at 1.67 million cycles and the corresponding surface condition of the contacts at the end of the test. The ECR trend for unlubricated contacts involved two regions: (1) region LW, indicative of low wear and characterized by a low and stable ECR and lower values of COF, and (2) region HW, indicative of high wear and following region LW, exhibiting a decrease in ECR, and presenting intermittent ECR spikes and an increase in COF. It was observed that ECR in region LW was close to the values measured during stationary test conditions at the beginning of the test.

The introduction of two wear regions gives a quantitative estimation of the expected number of cycles, after which the rate of wear increases between the contacts when observing both the ECR and COF behavior. Region LW has comparatively little wear and is indicated by a COF less than 1 and accompanied by stable ECR. A censored test performed during this region showed the contacts experienced mostly adhesion surface wear with gold-on-gold interaction; the surface wear volume and area were low. However, region HW showed the onset of unstable ECR with intermittent ECR spikes due to the reactive contact metal oxides interfering between the surfaces and direct reactive metal asperity interaction. Additionally, COF went high, indicating higher surface wear due to increased contact friction and subsequent shear, leading to the exposure of underlayers at some wear sites or zones. The continuous occurrence of intermittent ECR spikes above 10 Ω eventually led to the contact failure as per the test end condition.

Two parameters were used to differentiate the wear regions: (1) the in-situ ECR measured at the set contact load during the fretting test and (2) the ECR_{init} acquired at 10 gf during the stationary test. Among all the tests performed for the unlubricated case, for a region to be termed LW the variation between ECR during the fretting test and ECR_{init} was within ± 5 mΩ, resembling stable ECR. Consequently, when the ECR variation went outside the ± 5 mΩ bounds, it indicated region HW with ECR dropping below ECR_{init} - 5 mΩ. As per this condition, unlubricated contacts showed an average duration of 10,000 cycles (23,000 cycles for this test) until the onset of region HW.

The effects of fretting; wear, and corrosion in unlubricated contacts resulted in the wearing of protective gold-plating and the exposure of underlayers on both the pin and the flat surface. EDS analysis of the pin and the flat in Fig. 3 showed the absence of gold in most of the wear regions, the presence of nickel and copper on the pin surface, and nickel-palladium alloy and copper on the flat. Surface mapping of both the contacts detected copper, which is the substrate metal; however, point analysis at several wear locations on the pin detected nickel as well. This was indicative of nickel underlayer thinning at some wear sites, while at other locations, even the underlayer was worn off to expose the copper. For the flat, point analysis at various locations confirmed the presence of a nickel-palladium underlayer where copper was detected as well, indicating underlayer thinning. Due to the exposure of reactive metals—nickel, palladium, and copper—the pin was found to be oxidized with the metal-oxide debris collected primarily at the central dimple, as seen in the pin's SEM image. Additionally, the flat showed some oxygen mapping where nickel was present, indicating metal-oxide formation. The oxides were primarily observed as wear debris around the wear zone periphery. The exposure of underlayers and reactive metal oxidation resulted in the observed high values of ECR.

3.1.2 PFPE-Lubricated Contact

The tests that did not terminate in region LW progressed toward region HW, marked by a significant decrease in ECR below the stationary test condition value for the respective cases, the appearance of intermittent ECR spikes, and severe surface wear. Contacts in this region operated primarily in the boundary lubrication regime and were characterized by higher COF (above 0.4) and increased contact surface degradation. Fig. 4 shows ECR, COF, and surface wear of a test on a PFPE–A lubricated contact that stopped after entering region HW. Fig. 5 and Fig. 6 show the same for a test on PFPE–B and PFPE–C (2%) lubricated contacts. The duration of region LW was found using the same criteria as in the case of the unlubricated contact. PFPE–A showed an average of around 172,000 cycles, PFPE–B around 69,000 cycles, and PFPE–C (2%) around 81,000 cycles before entering region HW. The PFPE lubricants delayed the start of region HW by 11 times on average compared to the unlubricated contacts. As a result, PFPE–A lubricated contacts completed around 1.5 million fretting cycles on average, with one test lasting for 2.26 million fretting cycles; PFPE–B completed around 1.2 million fretting cycles, and PFPE–C (2%) completed close to 643,000 cycles (maximum completed cycles was 877,250) before meeting the test end criteria.

For the tests that did not terminate in region LW but rather in region HW, EDS analysis of the flat and pin surfaces for PFPE-lubricated contacts detected the presence of the nickel underlayer on the pin surface and the nickel-palladium underlayer on the flat surface; the analysis resulted in occasional detection of copper on either surface at some regions of the wear track. Fig. 7 shows SEM images of the pin and the flat surface and the respective EDS mapping for the PFPE–A test. On both the contact surfaces, the wear zone reveals the underlayer metals; however, concentrations of both the PFPE elements—oxygen and fluorine—were minimal at those locations, indicating the removal of the lubricant, effective metal-metal interaction, and eventual material wear. Point analysis of the pin confirmed the presence of a very thin gold layer over the regions where nickel was detected and the minute presence of nickel-palladium as a result of the underlayer's material transfer from the flat. The absence of nickel exposure on the pin's surface ruled out nickel's oxidation and its oxide debris formation. Similarly, point analysis for the flat confirmed a thin gold layer over the exposed areas where nickel-palladium was detected and the presence of underlayer materials where copper was present. For the PFPE−B and PFPE−C cases, the flat and pin showed similar surface analysis with a thin gold layer over the underlayer metals and the absence of any oxidation. However, for PFPE−C, both the element mapping and point analysis on the pin confirmed the detection of nickel and oxygen and the absence of fluorine and carbon at some wear sites, indicating the probable oxidation of the pin.

Some PFPE-lubricated contact tests terminated in region LW since the rise in ECR during the instability was higher than 10 Ω multiple times and caused the tests to fail. For those cases, the surfaces were observed to have minimum wear, gold-over-gold wear condition, and considerable lubricant film between them. Fig. 8 shows the test with a PFPE−A lubricated contact that stopped in region LW. It was found that the high ECR did not sustain when the measurements were taken at 0.5 Hz, and COF increased between the contacts as well. Figure 8's ECR and COF vs. displacement graph shows the reduction in ECR measured over the 80-micron wear track at 0.5 Hz (slow speed) immediately after the contact failed at 153,100 cycles (i.e., when ECR at 50 Hz was observed to be higher than 10 Ω for the fifth time). High values of ECR during 50 Hz (i.e., at high speed) and lower ECR measurements at 0.5 Hz demonstrated the effect of hydrodynamic lubrication at increased sliding velocities. Accordingly, an increase in COF from a value of around 0.1 during the start of the displacement along the wear track to 0.2 upon the displacement's completion was also observed due to the reduction in velocity. As a result, the lubricating film could bear the contact load at a high speed of 50 Hz and minimized effective asperity contact. However, its load-bearing capability reduced as the speed decreased to 0.5 Hz, often allowing more metal-to-metal interaction (Stribeck's effect). Hence, some PFPE-lubricated tests failed in region LW due to the onset of hydrodynamic lubrication, which increased ECR abruptly while minimizing the surface degradation.

3.1.3 PAO-Lubricated Contact

In general, the PAO-based lubricants demonstrated low and stable electrical contact resistance for longer durations when compared to the unlubricated and PFPE-lubricated contacts, except for PAO−B, which initially showed unstable ECR behavior for about 10,000 cycles only. However, the ECR instability was minimized or eliminated when a 2% (w/w) solution of PAO−B in mineral spirits was deposited onto the flat to obtain a reduced lubricant thickness. All PAO-based lubricated contacts had a similar range of cycles during which the in-situ ECR while fretting decreased to the ECR measured at the stationary test condition, ECR_{init}, analogous to the unlubricated contact case. This region, also called region LW, was followed by a transition region (TR) characterized by low and stable ECR with decreasing ECR behavior as the cycles increased. TR—defined by an increasing rate of surface wear, wear volume, and COF than region LW—was present for at least four million cycles in all the tests before the contacts failed. In some cases, it continued until the test end condition of 15 million cycles. For both PAO−A and PAO−B lubricated contacts, one test out of four failed. Fig. 9 and Fig. 10 show ECR, COF, and contact surface conditions at the end of tests for PAO–A and PAO–B lubricated contacts, respectively. Each of the remaining three tests for each case ran until 15 million fretting cycles without showing any significant increase in ECR throughout the tests. For the PAO–B (2%) case, all four tests failed at less than one million fretting cycles.

For quantification analysis analogous to the unlubricated contact case, a region HW was defined as well. It was characterized by a sharp decrease in the ECR behavior while fretting and COF shooting beyond a value of 1 during the HW onset, often extending in the range of 1.5 and 2.5 on average before the test end conditions were met. It was observed that all the PAO-lubricated contact tests that did not fail in TR experienced a drop in ECR of around 10 mΩ compared to ECR_{init} before entering region HW. Hence, an ECR change of more than 10 mΩ during the in-situ fretting determined the onset of region HW, often characterized by increased surface wear compared with contacts failing in TR. This was also confirmed by the increasing COF and decreasing ECR trends and surface analysis post-test end. On average, among all the tests, PAO–A showed six million cycles, PAO–B showed four million cycles, and PAO–B (2%) showed around one million cycles before entering region HW.

EDS analysis of both the pin and the flat surfaces shown in Fig. 11 ruled out the oxidation of the reactive underlayer metals (nickel and nickel-palladium) since the oxygen mapping was absent at locations where the reactive metals mapping was detected for both surfaces. Additionally, no copper was exposed by wear on either of the contacts; this finding was confirmed using point analysis. For the pin, nickel was exposed due to the major gold transfer to the flat surface; however, point analysis confirmed the presence of a thin gold layer over nickel mapping (which supported the absence of oxidation) and stable ECR during region LW and TR. As for the flat, point analysis detected nickel-palladium alloy at a few locations, but it was heavily covered with gold, primarily due to the material transfer phenomenon. The carbon map for both surfaces pointed to the oil's adherence around the wear zone and throughout the wear tracks.

3.2 Comparison between Lubricants: Reliable Contact Life

Two-parameter Weibull analysis was used to compare the cycles to failure data for all the lubricated and unlubricated tests, as shown in Fig. 12. The analysis indicated that PAO-based lubricated contacts represented a higher contact life and were the most reliable, with survival probabilities of 99.9% for PAO–A, 87.5% for PAO–B, and 62.5% for PAO–B (2%) at 10 million fretting cycles. The survival probability of all the PFPE-lubricated contacts and the unlubricated ones was less than 1% calculated at 10 million cycles; however, at two million cycles, PFPE–A had 41.7%, PFPE–C had 30%, and PFPE–B had 25% as their respective survival estimates. PFPE–C (2%) was the least reliable, even at one million cycles. The evaluation of reliable performance at two million cycles was performed to compare the PFPE-lubricated contacts among themselves and with the unlubricated contact case. It shall be noted that the means of the different lubricated cases were not statistically significant, and the analysis was based on a small sample dataset.

3. 3 Effect of Lubricant Thickness on Fretting Performance

Two different film thicknesses of PFPE–C and PAO–B lubricants were achieved by preparing a solution capable of dissolving the respective lubricant type and altering the solution's net concentration with dilution. For a fixed solution volume, increasing the lubricant concentration increased the obtained film thickness on the flat after the spin coating process. Two 2% solutions were made, one containing PFPE–C and the other containing PAO–B, the thicknesses of which were confirmed once the solutions were applied. Although the applied film thickness was different from the actual film thickness when the surfaces mated, the difference in film thickness due to change in concentration affected the contact's performance. On average, thicker lubricating films close to 1 micron resulted in delaying the contacts entering region HW, where contact failure later occurred. Fig. 13 shows how using different lubricant thicknesses can affect the average number of cycles required by the coated contacts before entering region HW for each case. The error bars show the minimum and maximum cycles observed.

The film thickness deposited on the flat for PFPE–C (100%) without any dilution was 30 times thicker than the thickness of PFPE–C (2%). All of the PFPE–C (100%) lubricated contacts failed in region LW due to a surge in ECR, with no significant wear on the surfaces, whereas PFPE–C (2%) lubricated contacts resulted in one failed test in region LW while the remaining contacts failed in region HW. The PFPE–C (100%) lubricated contacts endured five times as many cycles before entering region HW, on average, compared to the PFPE–C (2%) lubricated contacts—although the difference was not statistically significant for the limited set of data. The film thickness obtained for the PAO–B (100%) lubricated contact was about 32 times thicker than PAO–B (2%), and the former contacts underwent four times the average number of cycles before entering the region HW. Thicker PAO–B lubricant film introduced ECR instability for about 10,000 initial fretting cycles, as seen in Fig. 14, which was not observed for PAO–B (2%) cases.

3.4 Effect of Viscosity

The kinematic viscosities of PAO-based lubricants were at least one-third of the PFPEs. While PAO lubricants showed higher contact life and larger duration of cycles during which ECR was stable compared to the PFPE lubricants, kinematic viscosity itself cannot solely account for the observed contact's fretting performance. While the PAOs' lower kinematic viscosities improved the contacts' performance and their useful life, this was not the case when the different PAOs were compared. PAO–A had a higher viscosity among the three tested; however, they also showed higher reliability and increased cycles to failure. This suggests that a lubricant's chemistry has a significant role to play in the observed differences in contact performances. On the other hand, kinematic viscosity was found to influence the occurrence of the hydrodynamic effect in PFPE-lubricated contacts. PFPE-based lubricant with a higher viscosity, like PFPE–C (2%), would show hydrodynamic behavior sooner than a lubricant like PFPE–B having a lower viscosity value. For quantification of the effect, the hydrodynamic behavior was observed when ECR was greater than 100 mΩ. During the initial 1,000 fretting cycles, ECR instabilities beyond 100 mΩ threshold were not considered to contribute to this effect since the instabilities resulted due to less effective contact area and an initial thick lubricant layer present between the mated contacts causing the ECR to increase. The fretting motion during 1,000 cycles dispersed the lubricant at the contact site and increased the effective contact area, which was also seen from the decreasing ECR values post the starting of the test. This was confirmed from the PAO–B lubricant that a thicker film could introduce such ECR instabilities at the beginning of the test for the initial 1,000 cycles, which over time reduced once the effective contact area increased. Fig. 15 shows how kinematic viscosities of PFPE-based lubricants influence the number of cycles completed before the hydrodynamic behavior of the film appears.

Kinematic viscosity is a lubricant property that is indicative of the resistance to relative motion between adjacent layers in a liquid. Its effect is primarily observed during the hydrodynamic mode of lubrication. A lubricant with higher viscosity possesses a larger load-bearing capacity under the same conditions of speed and load. In the case of PFPE-lubricated contacts, PFPE–C was more viscous, making the lubricated contacts susceptible to shift from boundary lubrication to the hydrodynamic mode of lubrication in shorter time periods than the other two PFPEs having lower kinematic viscosities. Less viscous PAO-based lubricants did not show any hydrodynamic effect later once the initial ECR instability was minimized after a few thousand cycles, as in the case of PAO–B (100%).

4 Discussion

The unlubricated and different lubricated contacts showed distinguishable regions in the ECR trend that correlated with the observed COF experienced by the contacts. The different regions—LW, TR, and HW—identified primarily in the ECR trends are indicative of the surface condition or degradation between the contacting members that affect the contact's performance. Region LW, characterized by low COF values and ECR close to stationary test condition values, indicates a lower rate of wear. In region LW, the surfaces experience the removal of any adventitious layer followed by adhesive wear with significant material transfer from one surface to another. As the fretting progress, the adhesive wear process starts, resulting in wear debris particles in the form of gold prows in between the surfaces. These particles, as the work-harden, result in the start of abrasive wear, which is when the dominant wear process increases the rate of surface wear and is sometimes accompanied by ECR instabilities. The end region, HW, indicates severe contact surface wear and is often characterized by a noticeable decrease in ECR, the appearance of intermittent spikes, and oftentimes higher COF or contact friction that can cause electrical contact failure. The transition from LW to HW in PAOs is the TR that is indicative of the transition from purely adhesive wear process to abrasive wear process. This duration or period of cycles during region LW and TR informs our understanding of which lubricant type or case can reduce the wear rate.

The unlubricated contacts had a region LW with an average duration of about 10,000 fretting cycles and immediately transitioned to region HW without any noticeable TR. Unlubricated contact test failures were mostly due to the oxidation of reactive underlayer metals exposed during severe wear and the insulating metal oxides formed during the process. Oftentimes, this wear debris caused abrasive wear and was accountable for the increase in ECR in the form of ECR spikes, leading to electrical discontinuity. PAO-lubricated contacts showed a similar duration of 19,000 cycles during region LW, but TR was determined with low and stable ECR extending to at least a million fretting cycles, often delaying the onset of region HW by a few million cycles during the tests. Lastly, PFPE-lubricated contacts had an increased region LW duration of about four times that of the unlubricated contacts, but like the unlubricated case, they also did not show any noticeable transition region toward HW.

From all the tests conducted for different lubricant cases as well as the unlubricated case, it was quantitively seen that PFPE-lubricated contacts sustained five times more fretting cycles than the PAO-lubricated and unlubricated contact tests during the region LW; however, they failed early when the COF was high, and contact surface degradation became severe – the characteristics of region HW. In contrast, PAO-lubricated contacts sustained an extended transition period of at least a few million cycles when progressing from the low-wear region to the high-wear region. In short, on average, among all the tests performed, PAO-lubricated contacts sustained 400 times more the number of fretting cycles than unlubricated contacts, and more than 36 times the number of fretting cycles than PFPE-lubricated contacts before entering the high wear region.

PFPE lubricants proved to be better in resisting surface wear at low contact load conditions than PAOs due to the larger duration of region LW; however, ECR was often unstable that led to the failure of some test cases. The ECR instabilities were characterized by consistent ECR increase at high speed of 50 Hz with a sudden decrease at a slow speed of 0.5 Hz. This ECR behavior negated boundary lubrication but represented hydrodynamic mode of lubrication, and COF values during the entire fretting duration were lower compared to PAOs and the dry contacts. The dependence of COF on the state of contacting surfaces is consistent with other studies [1][15][16] that compare COF as a measure of wear resistance. However, PFPE lubricants were not as effective as PAOs in delaying severe wear once the wear debris started interfering between the contacts. PAO lubricants showed a tendency to remove the wear particles from the effective contact area, thus delaying the onset of severe wear.

The viscosity of a lubricant can significantly affect contact performance, and test parameters like the pertinent contact load and fretting frequency have a role in deciding the viscosity range suitable for the desired application. According to Antler [1], PFPE lubricants with a viscosity higher than 1000 cSt resulted in hydrodynamic effects under contact loading of 49 cN (50 gf); meanwhile, in this study, hydrodynamic effects were observed with PFPEs having a viscosity higher than 100 cSt for a contact load of 9.8 cN (10 gf) and frequency of 50 Hz, but not for 0.5 Hz. For the fixed test parameters described above, PFPE lubricants can have a viscosity limit above which they show hydrodynamic effects during fretting. The thickness of the applied lubricant film can also affect the wear resistance, which is in conformance with other studies [17][18]. A thicker film improves contact life; however, it can also introduce ECR instability at the test's beginning, as seen in the case of PAO–B lubricant deposited as neat or 100% concentration. The instability resulted from the lubricant's tendency to bear the contact load at a high fretting speed compared to a lower speed of 0.5 Hz, where the ECR was stable. Additionally, the lubricant's dispersion at the contact site, decreasing its applied thickness and increasing the contact's effective area, helped make the ECR stable after few cycles. Such behavior was absent with a thick film of PAO–A with higher kinematic viscosity than PAO–B lubricant.

5 Conclusions

Gold-plated contacts are prone to surface degradation – wear and corrosion, and fretting can cause unexpected contact failure resulting in their poor useful functional life. For high contact load applications, lubricating electrical contacts using synthetic oil lubricants help prevent field failures; however, emerging low-load contact applications requiring fewer centiNewtons of contact forces still face issues in controlling the contact surface degradation even with noble gold used as a protective contact plating.

The chemistry of a lubricant plays an essential role in a contact's fretting performance. For lightly loaded contacts at 9.8 cN (10 gf) of contact load, both the PFPEs and PAOs improved the contact life – higher fretting cycles to failure with relatively less contact surface degradation than dry or unlubricated contacts. However, a comparison between PAO-, and PFPE-lubricated contacts concluded the following:

1. PAOs were better at minimizing contact failures and improving the contact's life for a larger duration of fretting cycles than the PFPEs, suggesting their selection for lightly loaded contact applications.
2. Within the tested PAOs, once the fretting motion during the initial 1,000 cycles had evenly dispersed the applied lubricant at the contact site minimizing initial ECR fluctuations, all the PAOs thereafter maintained stable ECR values of less than 100 mΩ for at least 10 million cycles, with the exception of a thinner PAO having lower contact resistance values for 1 million cycles.
3. PAOs sustained a higher number of fretting cycles before the contacts started to experience severe surface wear instead of PFPEs that comparatively sustained more cycles during the initial contact wearing.
4. PFPEs showed a hydrodynamic mode of lubrication responsible for early contact failure at a high fretting frequency (50 Hz); however, their wear resistance relative to the PAOs was found to be better. The performance observation of PFPEs at low contact loads contradicts the published literature that cites their usefulness in improving contact life at higher loads.
5. Statistically, at 10 million fretting cycles, the PAOs proved to be at least 50% reliable in improving the contact life, with one PAO showing more than 99% reliable life. On the contrary, all the tested PFPEs were less than 1% reliable.

Kinematic viscosity and the applied thickness of a lubricant also favor their suitability for any electrical contact application. Highly viscous PFPEs with kinematic viscosities around 100 cSt or higher increased the susceptibility of lubricated contacts to experience hydrodynamic mode of lubrication and rendered them inappropriate for low-load electrical contact applications at high fretting frequency. On the other hand, PAOs with kinematic viscosities less than 50 cSt maintained boundary lubrication with lower ECR values for longer-duration fretting cycles with the fewest test failures, supporting their applicability for lower contact loads. In line with the published literature, it was found that a thicker lubricant film can increase the wear resistance and life of lubricated contacts, as seen with the cases of different lubricant thicknesses for both the PFPEs and PAOs.

Declarations

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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References

[1] M. Antler, “The lubrication of gold,” *Wear*, vol. 6, no. 1, pp. 44–65, Jan. 1963.

[2] M. Antler, “Sliding studies of new connector contact lubricants,” *IEEE Trans. Components, Hybrids, Manuf. Technol.*, vol. 10, no. 1, pp. 24–31, Mar. 1987.

[3] B. H. Chudnovsky, “Lubrication of electrical contacts,” in *Proceedings of the Fifty-First IEEE Holm Conference on Electrical Contacts*, 2005, pp. 107–114.

[4] S. Noël, N. Lécaudé, D. Alamarguy, and L. Boyer, “Friction properties of perfluorinated polyethers for hot-dipped tin low-level separable electrical contacts,” *J. Synth. Lubr.*, vol. 19, no. 3, pp. 179–189, Oct. 2002.

[5] S. Noel, A. Brezard-Oudot, P. Chretien, and D. Alamarguy, “Fretting behaviour of tinned connectors under grease lubrication,” in *2017 IEEE Holm Conference on Electrical Contacts*, 2017, pp. 109–116.

[6] W. Freitag, “Wear, fretting and the role of lubricants in edge card connectors,” *IEEE Trans. Parts, Hybrids, Packag.*, vol. 12, no. 1, pp. 40–44, Mar. 1976.

[7] L.-G. Liljestrand, “A study of some factors influencing the wear resistance of lubricated gold contacts,” *IEEE Trans. Components, Hybrids, Manuf. Technol.*, vol. 6, no. 1, pp. 108–114, Mar. 1983.

[8] R. S. Timsit, E. M. Bock, and N. E. Corman, “Effect of surface reactivity of lubricants on the properties of aluminum electrical contacts,” *IEEE Trans. Components, Packag. Manuf. Technol. Part A*, vol. 21, no. 3, pp. 500–505, 1998.

[9] R. Holm, *Electric Contacts: Theory and Application*. Berlin ; Springer-Verlag, 1967.

[10] M. Braunovic, V. V. Konchit︠s︡, and N. K. Myshkin, *Electrical Contacts: Fundamentals, Applications and Technology*. Boca Raton : CRC Press, 2007.

[11] P. Van Dijk, “Some effects of lubricants and corrosion inhibitors on electrical contacts,” *AMP J. Technol.*, vol. 2, pp. 56–62, 1992.

[12] L. Kaushik, M. H. Azarian, and M. Pecht, “Effect of different lubricant films on contact resistance of stationary separable gold-plated electrical contacts,” *J. Mater. Sci. Mater. Electron.*, pp. 1–14, Jul. 2019.

[13] N. K. Myshkin and V. V. Konchits, “Evaluation of the interface at boundary lubrication using the measurement of electric conductivity,” *Wear*, 1994.

[14] T. Tamai, M. Yamakawa, and Y. Nakamura, “Effect of contact lubricant on contact resistance characteristics — Contact resistance of lubricated surface and observation of lubricant molecules—,” *IEICE Trans. Electron.*, vol. E99.C, no. 9, pp. 985–991, Sep. 2016.

[15] M. Antler and M. H. Drozdowicz, “Fretting corrosion of gold-plated connector contacts,” *Wear*, vol. 74, no. 1, pp. 27–50, 1981.

[16] M. Antler, “Electronic connector contact lubricants: The polyether fluids,” *IEEE Trans. Components, Hybrids, Manuf. Technol.*, vol. 10, no. 1, pp. 32–41, Mar. 1987.

[17] Y. L. Zhou and J. G. Zhang, “Investigation of the thickness of lubricant film on gold plated surface,” in *Electrical Contacts - 1998. Proceedings of the Forty-Fourth IEEE Holm Conference on Electrical Contacts (Cat. No.98CB36238)*, pp. 159–165.

[18] M. Antler, “Survey of contact fretting in electrical connectors,” *IEEE Trans. Components, Hybrids, Manuf. Technol.*, vol. 8, no. 1, pp. 87–104, Mar. 1985.

Figures

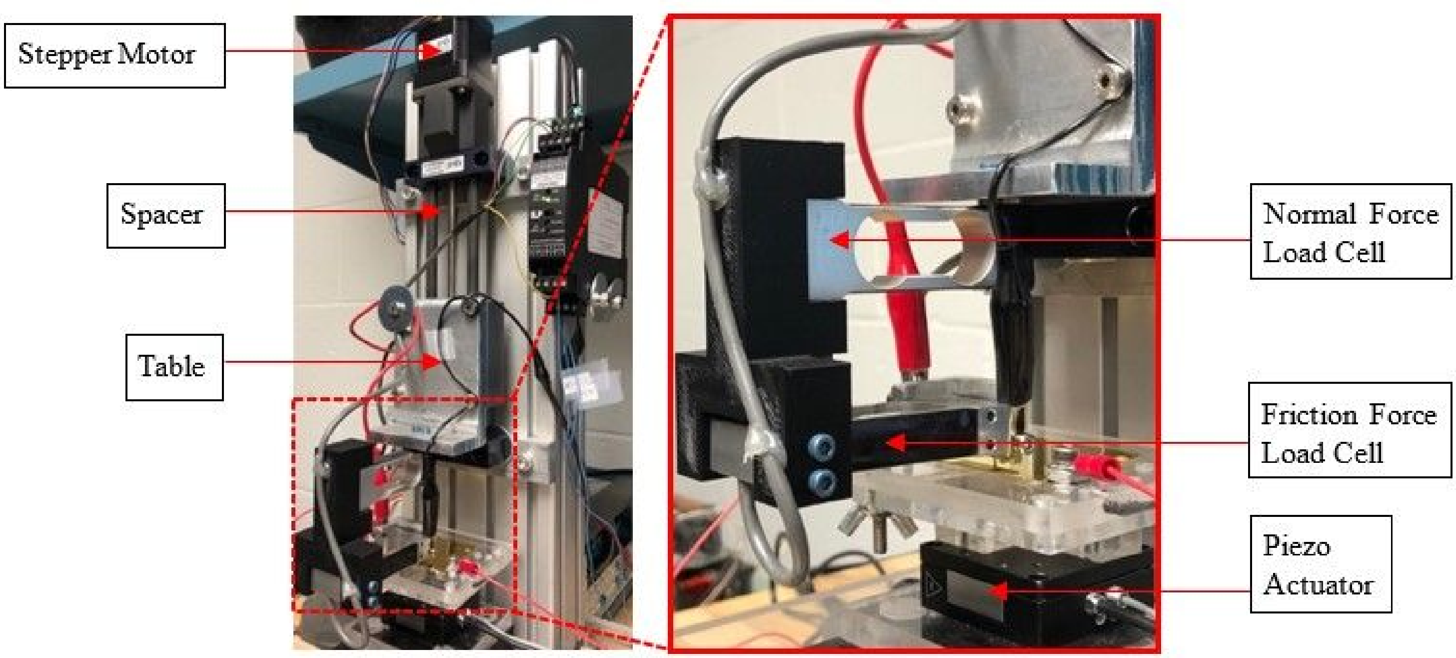

Figure 1

Contact Resistance Probe (CRP) setup showing different components of the system

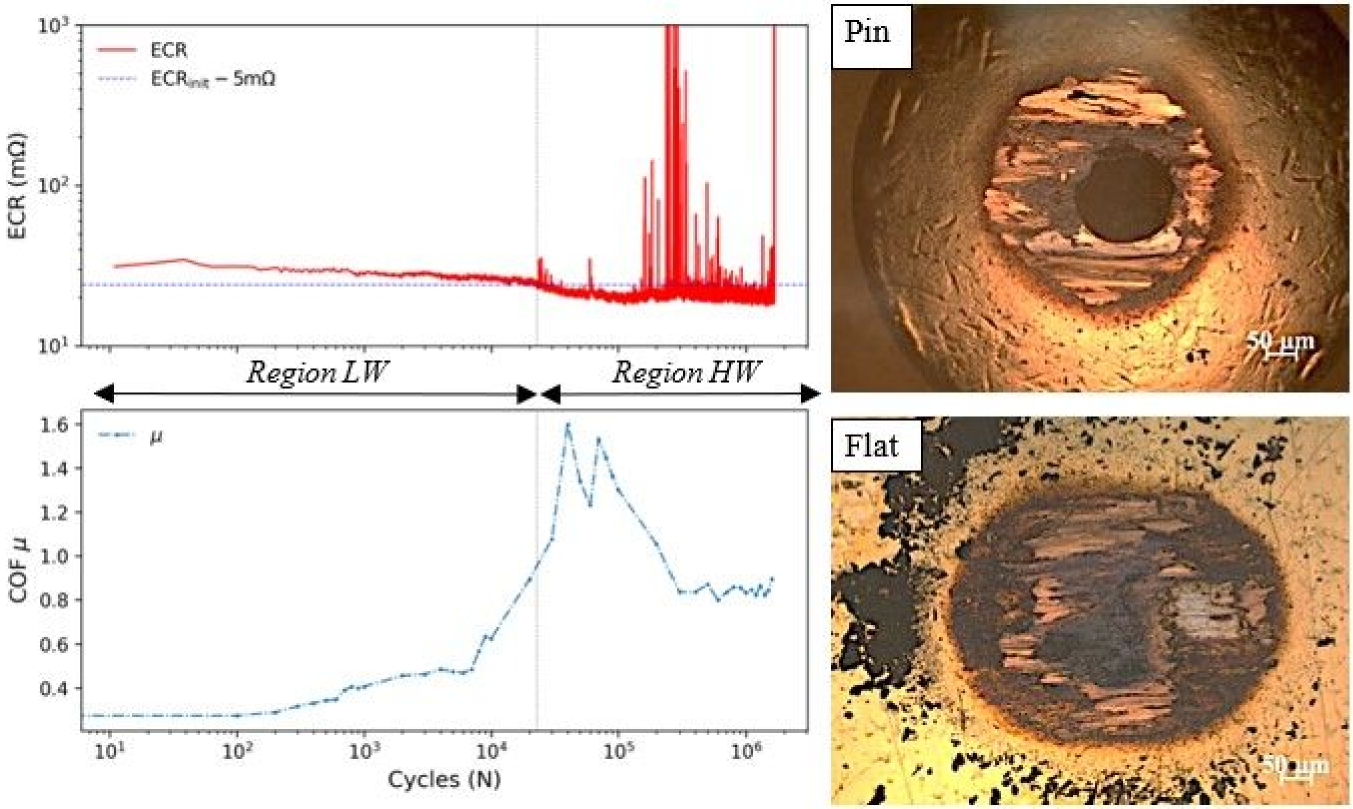

Figure 2

Unlubricated contact fretting performance at 1.67 million cycles; ECR, COF, and surface condition of the flat and pin, in anticlockwise direction

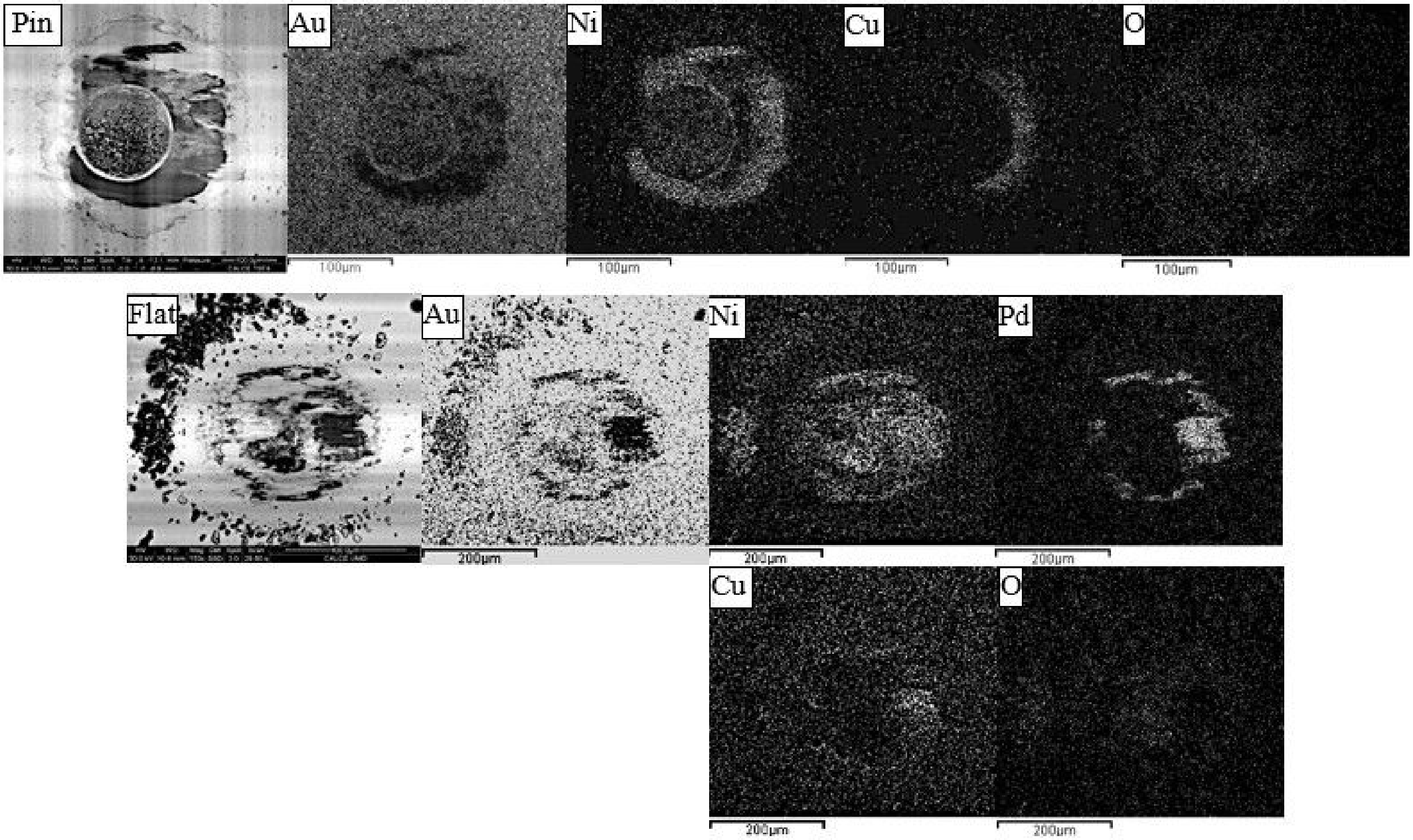

Figure 3

EDS mapping of the pin and the flat that endured fretting degradation until 1.67 million cycles

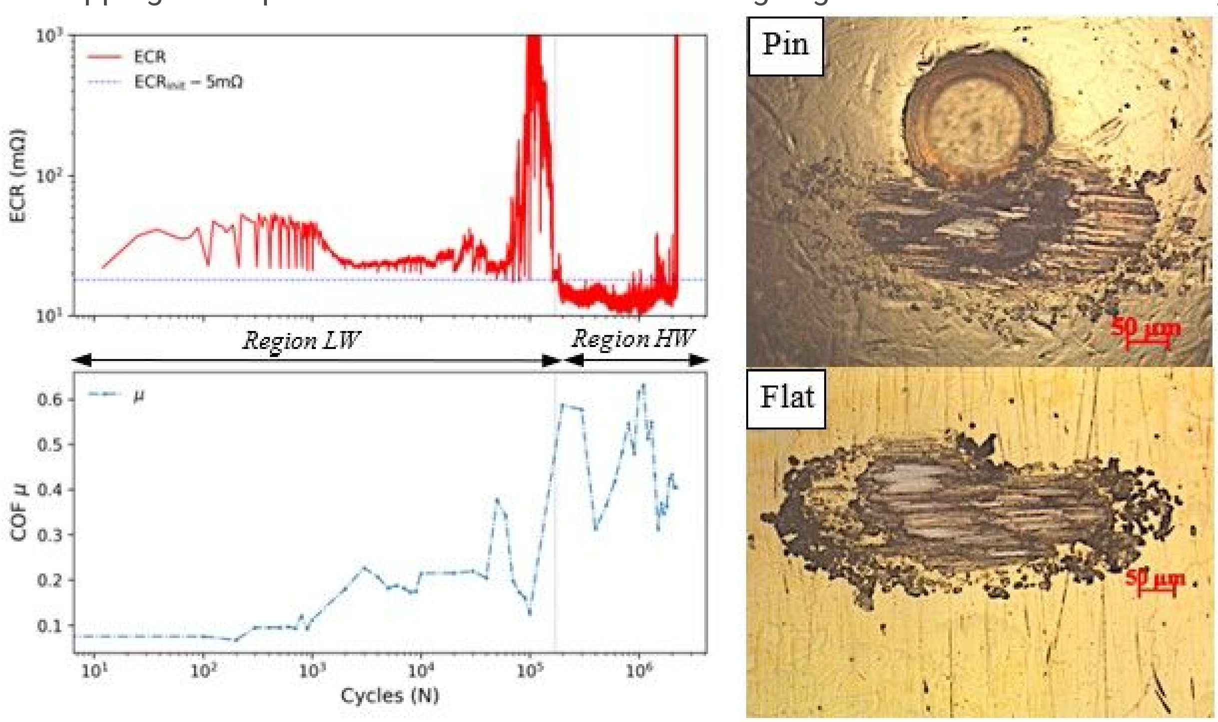

Figure 4

PFPE–A lubricated contact fretting performance at 2.26 million cycles; ECR, COF, and surface condition of the flat and pin, in anticlockwise direction

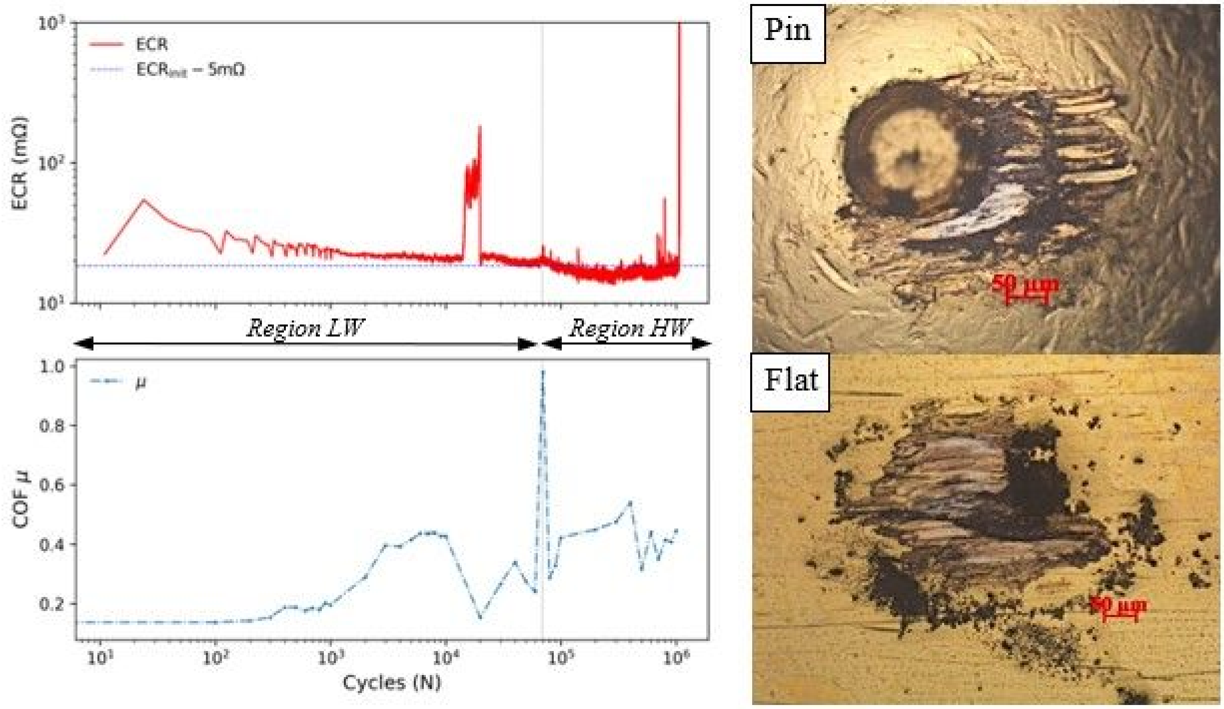

Figure 5

PFPE–B lubricated contact fretting performance at 1.06 million cycles; ECR, COF, and surface condition of the flat and pin, in anticlockwise direction

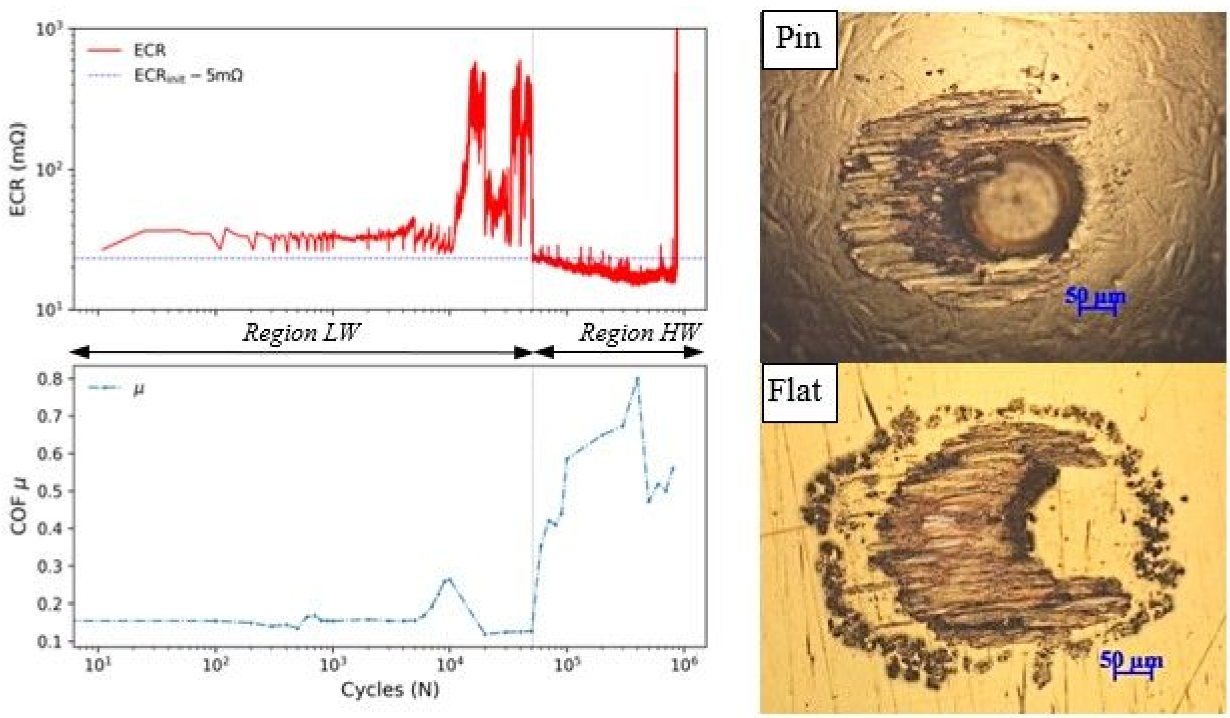

Figure 6

PFPE–C lubricated contact fretting performance at 877,250 cycles; ECR, COF, and surface condition of the flat and pin, in anticlockwise direction

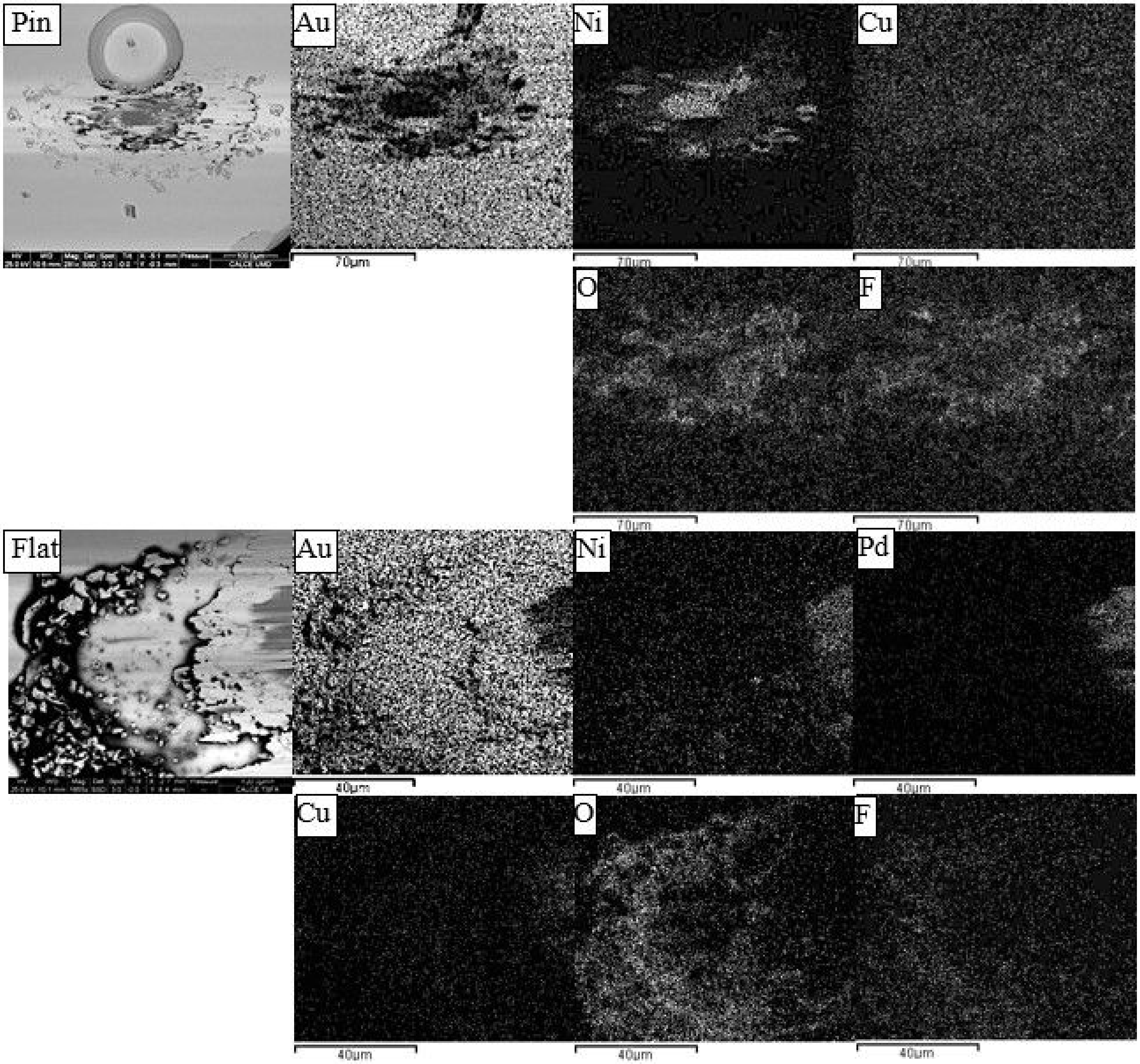

Figure 7

EDS mapping of PFPE–A lubricated flat and the used pin that endured fretting degradation until 2.26 million cycles

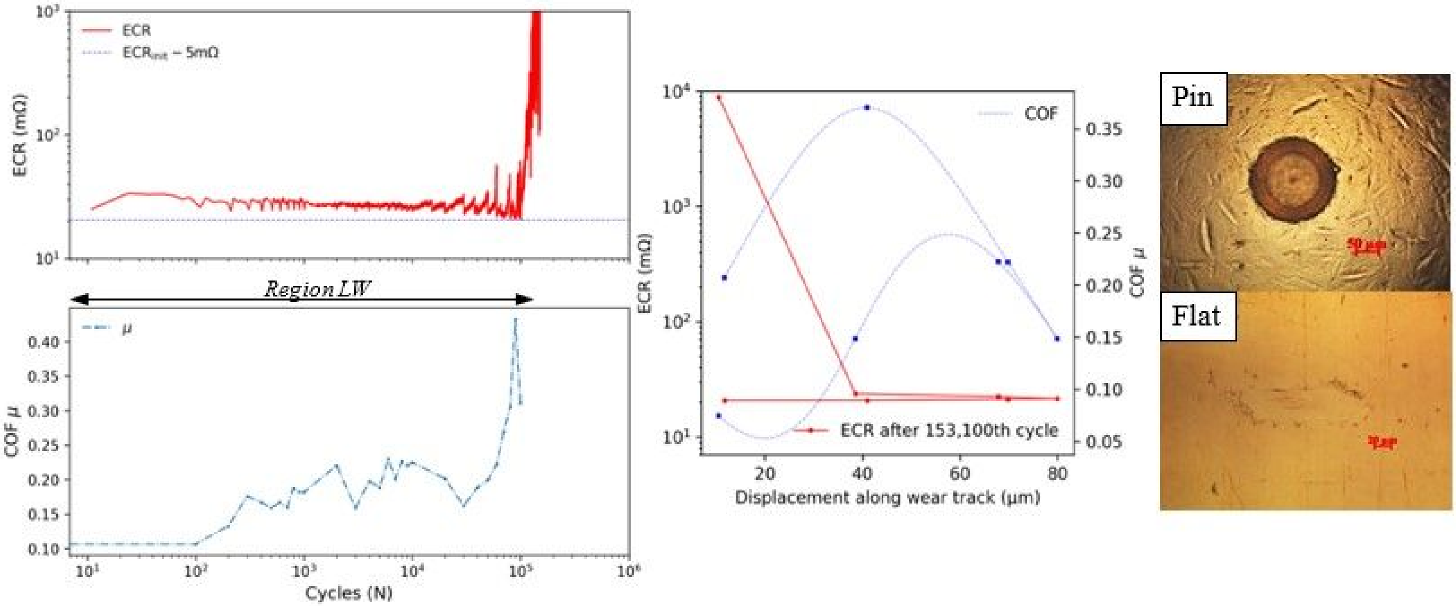

Figure 8

PFPE–A lubricated contact fretting performance at 153,100 cycles; ECR, COF, ECR and COF versus displacement after 153,100 cycles, and surface condition of flat and pin, in anticlockwise direction

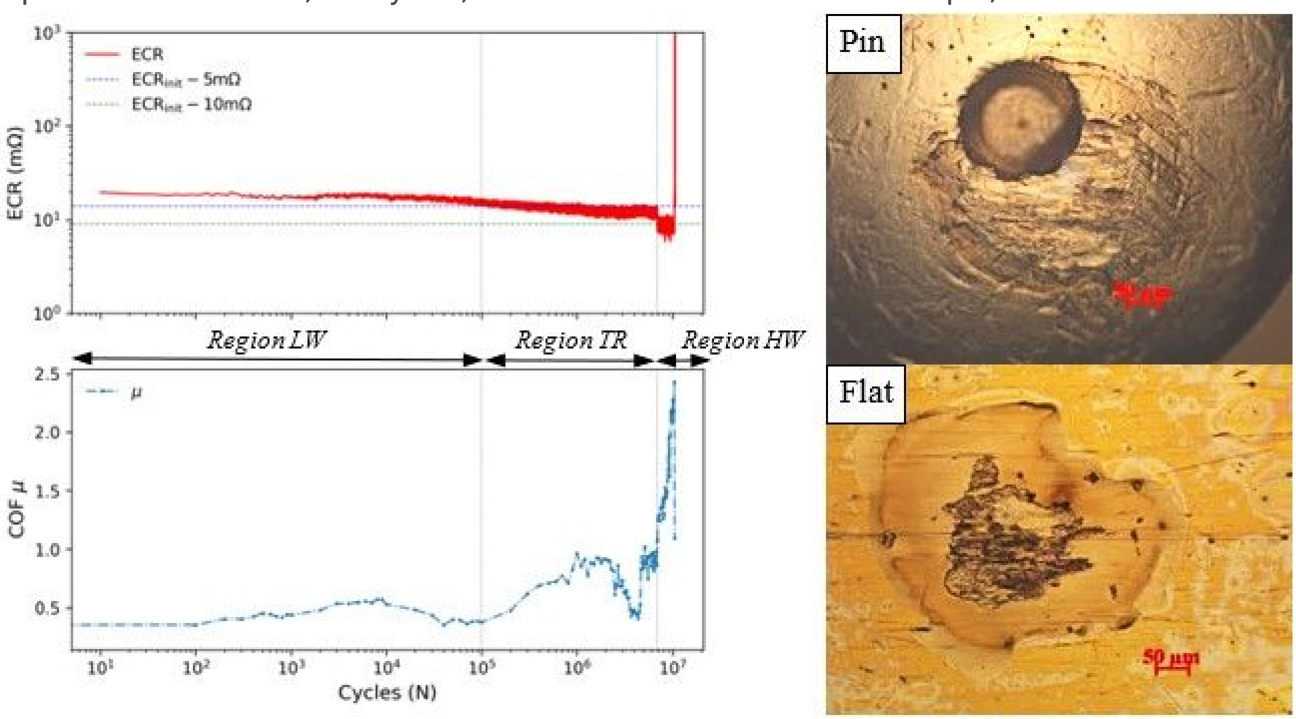

Figure 9

PAO–A lubricated contact fretting performance at 10.5 million cycles; ECR, COF, and surface condition of the flat and pin, in anticlockwise direction

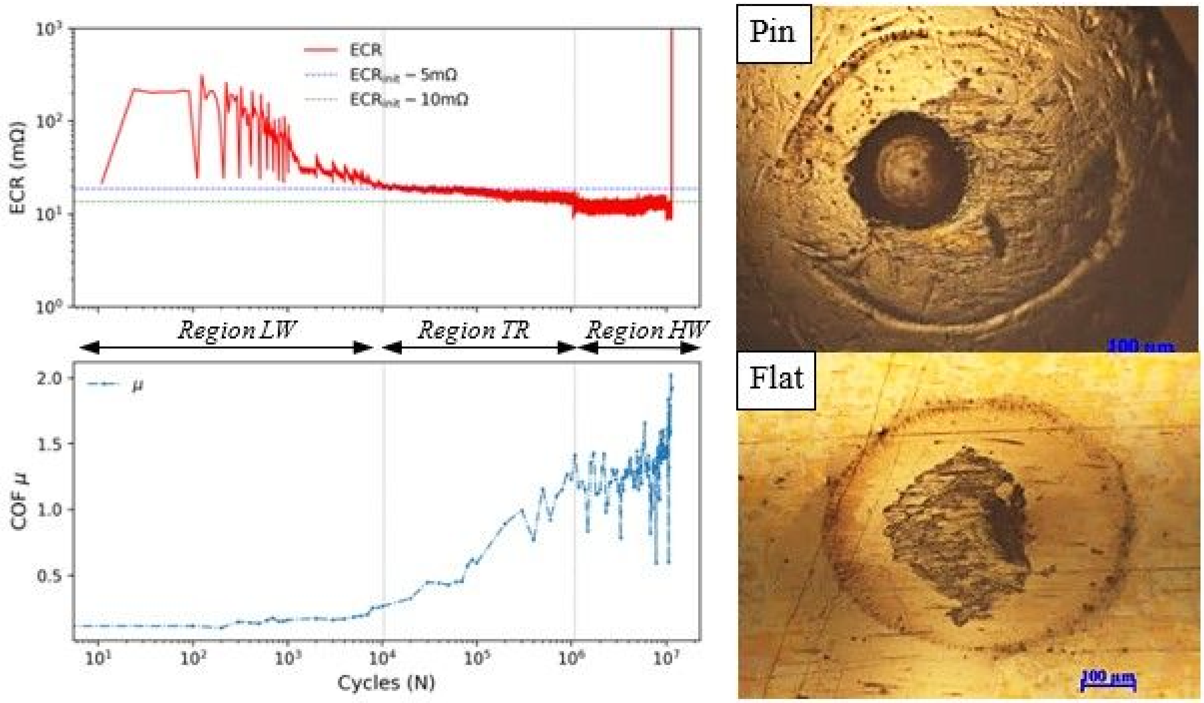

Figure 10

PAO–B lubricated contact fretting performance at 11.4 million cycles; ECR, COF, and surface condition of the flat and pin, in the anticlockwise direction

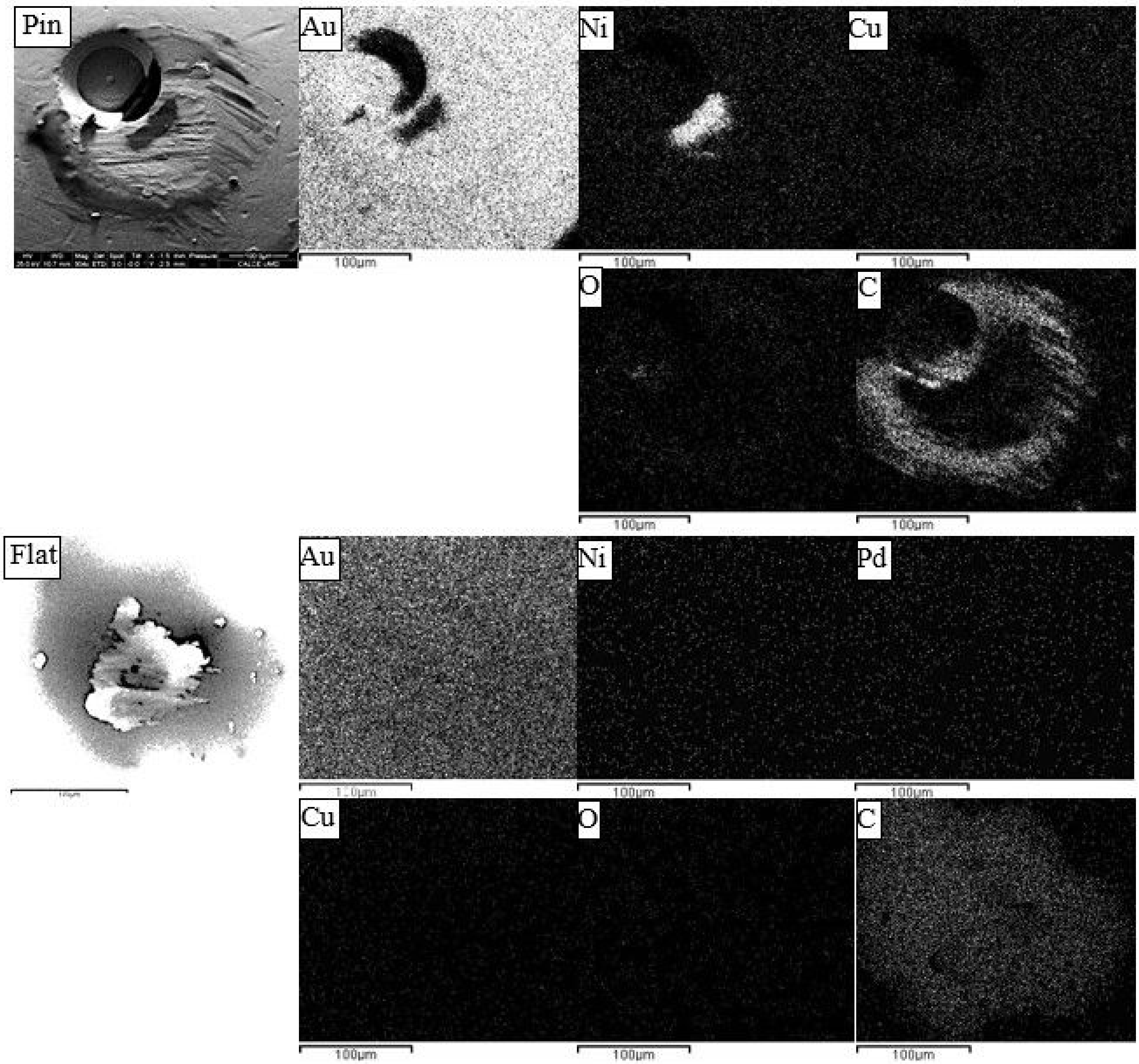

Figure 11

EDS mapping of PAO–A lubricated flat and the used pin that endured fretting degradation until 10.5 million cycles

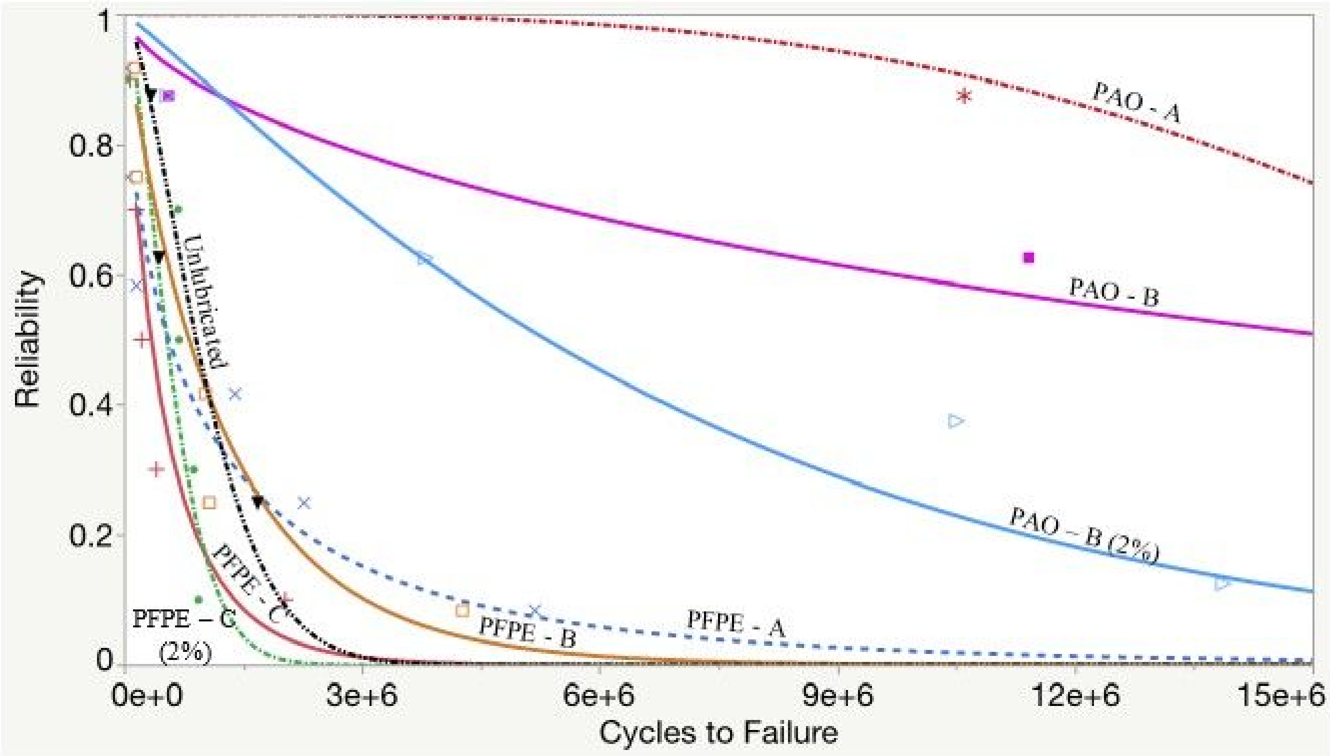

Figure 12

Reliability plots of the lubricated contacts under the fretting test conditions

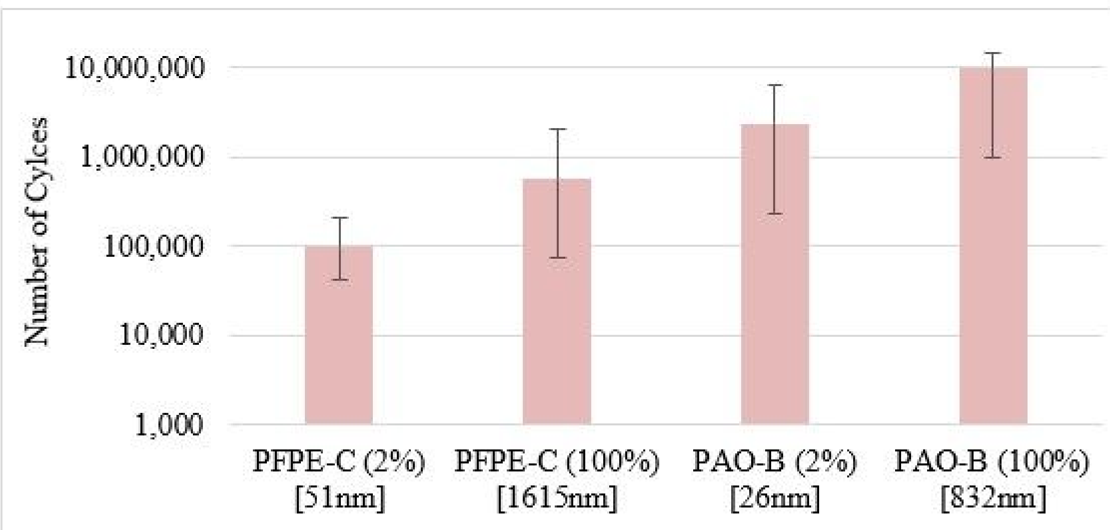

Figure 13

Effect of thickness of PFPE–C and PAO–B lubricant on the duration before reaching region HW

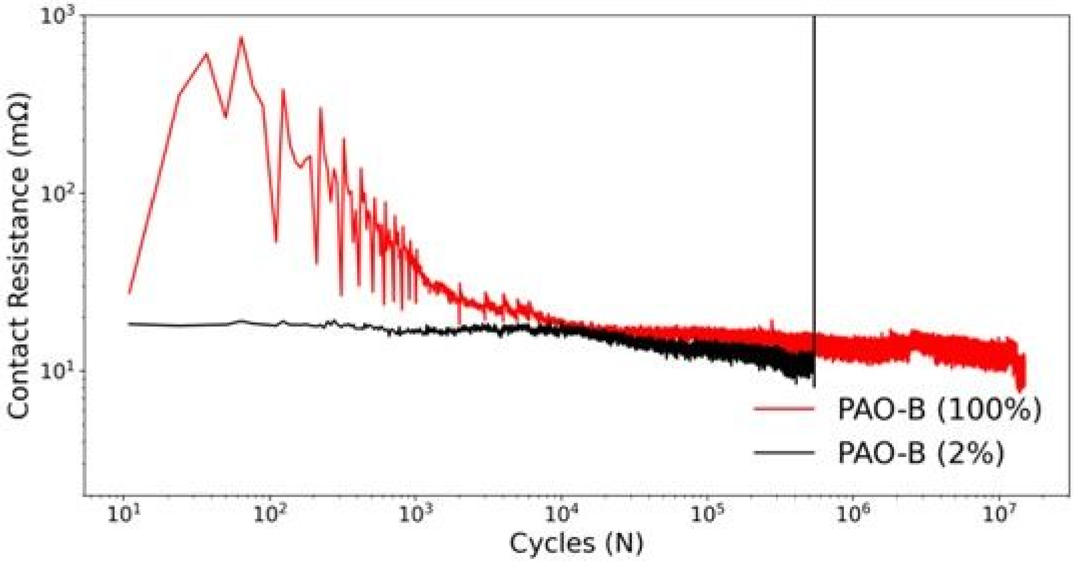

Figure 14

Comparison of ECR trend for PAO–B (100%) and PAO–B (2%)

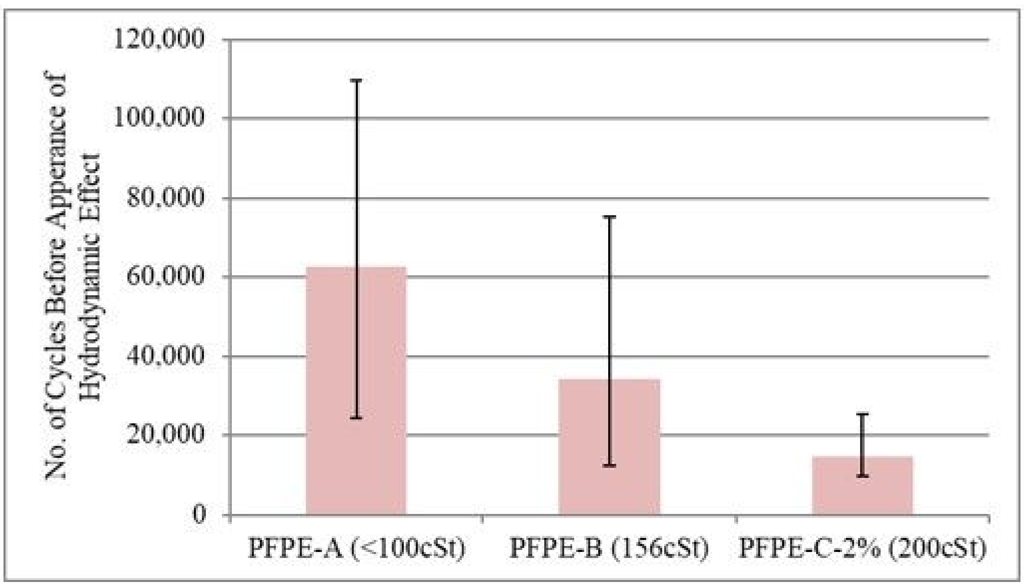

Figure 15

Effect of lubricant viscosity on the number of cycles taken for the hydrodynamic effect to appear in PFPE-lubricated contacts