Lubrication Concept Evaluated for Geared Actuators under Starved Conditions

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Abstract

Lubricant starvation leads to the risk of a shift in the lubrication regime from (elasto)hydrodynamic towards boundary conditons. Effective tribofilm formation is essential to limit surface damages in these conditions, but additive technology for space-grade lubricants is lacking. This work evaluates the feasibility of a novel type of multifunctional ionic liquid lubricant, for use with multiply alkylated cyclopentane (MAC). Actuator gearboxes are operated under starved conditions in nitrogen atmosphere to evaluate the effectiveness of the tribofilm forming lubricant (designated P-SiSO). The effectiveness of P-SiSO was evaluated from macro to micro scale in both surface and sub-surface analysis by use of microscopy (optical, interferometric, SEM) and X-ray microtomography (XMT), and mechanisms of effective lubrication are discussed.

Introduction

Conditions faced in robotic space exploration missions pose significant challenges to lubrication of complex mechanisms. Geared actuators operated in low temperatures require extensive preheating before startup [1], but once in operation they may suffer from lubricant starvation due to limited resupply of lubricant to the contact [2]. In vacuum conditions, native oxide layers quickly wear out and if the lubricant does not form a protective tribofilm, there is high risk of seizure. Perfluoropolyethers (PFPE) and multiply alkylated cyclopentanes (MAC) are heritage lubricants used in space applications. They both have benefits and drawbacks; the main benefit being outstanding resistance to outgassing, but their tribofilm forming properties are problematic. PFPE forms iron fluourides in tribocontacts, which prevents seizure but eventually degrades the system autocatalytically [3]. MAC on the other hand is a neat hydrocarbon, and is not generally tribochemically active. Additives are possible, but finding effective additives that are miscible and non-volatile is challenging, and few options are currently available. As space exploration missions are demanding increasing performance of mechanisms, new solutions are urgently required. This paper aims to establish the feasibility of using hydrocarbon-mimicking silicate forming ionic liquid (P-SiSO) as tribo-improving additive in MAC.

<u>Recent work on P-SiSO</u>

In our previous work [4], we described the molecular design of a hydrocarbon-mimicking synthetic lubricant composed of a tetraalkylphosphonium cation and trimethylsilalkylsulfonate anion, and found that it provides excellent lubricating performance under boundary lubrication conditions [5] as well as elastohydrodynamic conditions [6]. The hydrocarbon-mimicking structure enables miscibility with a range of hydrocarbon base fluids, while the ionic structure of P-SiSO enables reduced volatility. Surface analysis has shown that the excellent performance correlates with formation of a novel type of tribofilm, mainly based on silicate. Preliminary studies in vacuum tribometers and outgassing tests [7] have produced positive results and therefore the next step is to evaluate the lubricant under increasingly realistic configurations.

Materials and Methods

In this work, P-SiSO was evaluated in commercial off-the-shelf (COTS) geared actuators. Sintered metal gears, reduced lubricant fill, and reduced temperatures was employed to provoke lubricant starved

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conditions and accelerate damages. The main focus of the experiment is on the lubricants ability to limit surface and subsurface damage in the gears operated in lubricant starved conditions.

Concept lubricant

A concept lubricant was prepared by dissolving 0.4 wt% of a hydrocarbon-mimicking ionic liquid (tetraalkylphosphonium trimethylsilaalkylsulfonate) [4] in multiply alkylated cyclopentane. Adequate performance with regards to thermal vacuum outgassing and solubility was recently demonstrated by the this lubricant [8], which we hereafter designate as P-SiSO. Two reference lubricants were employed during this work; Synthetic Oil 2001a, a multiply alkylated cyclopentane supplied by Nye Lubricants, Inc. (Fairhaven, MA), and Fomblin Z25, a perfluoropolyether supplied by Solway S.A. (Brussels, Belgium). The reference lubricants are designated as MAC and PFPE respectively. Neat tetraalkylphosphonium trimethylsilaalkylsulfonate was synthesized by Nisshinbo Holdings Inc. (Tokyo, Japan).

Actuator Gearbox Lubrication

The geared actuators consist of a planetary gearbox (GP32) and a DC-motor (RE30) with encoder and servo controller (ESCON 36/2), all acquired from Maxon Motor AG, (Sachseln, Switzerland). The gearboxes are 3-stage planetary gearboxes with 51:1 gear ratio, with max continous torque rating of 4.5 Nm. The servo controller can provide a maximum continous current of 2 A at 25 V, which corresponds to a max continous torque of 2.6 Nm, ensuring that the sintered steel gears are not mechanically overloaded. The gearboxes are dissasembled and cleaned, before relubricated with the test lubricants, as shown in Figure 1(a-b). The amount of lubricant applied is significantly reduced in order to provoke starved conditions; the original grease fill of 1.6 g is replaced with 0.060 g of test lubricant (5 µl to each planet gear and 15 µl to output bearing). After applying the test lubricant the gearbox is rotated under zero load at low speed (5 min at 800 rpm followed by 5 min at 4000 rpm) to achieve a consistent lubricant distribution within the gearbox.

Geared Actuator Test Rig (GATR)

A custom made geared actuator test rig (GATR), shown in Figure 1(c-d), was designed and manufactured for the purpose of evaluating the lubricants in a component scale experiment. In this setup, the actuator is mounted in a refrigerated chamber filled with N_2 gas. The main purpose is to subject the actuator gearboxes to operation in lubricant-starved and oxygen-reduced conditions in order to perform post test damage evaluation and boundary film analysis. The GATR is equipped with a dynamometer and temperature sensors in order to monitor effects on gearbox eficicency and temperature evolution while running the actuator against a braking torque. The efficiency is defined as the ratio of electrical power input, P_{in}, to mechanical power output, P_{out}. The power input can be determined by motor speed, current, and torque constant, while power ouput is determined by output speed and applied brake torque.

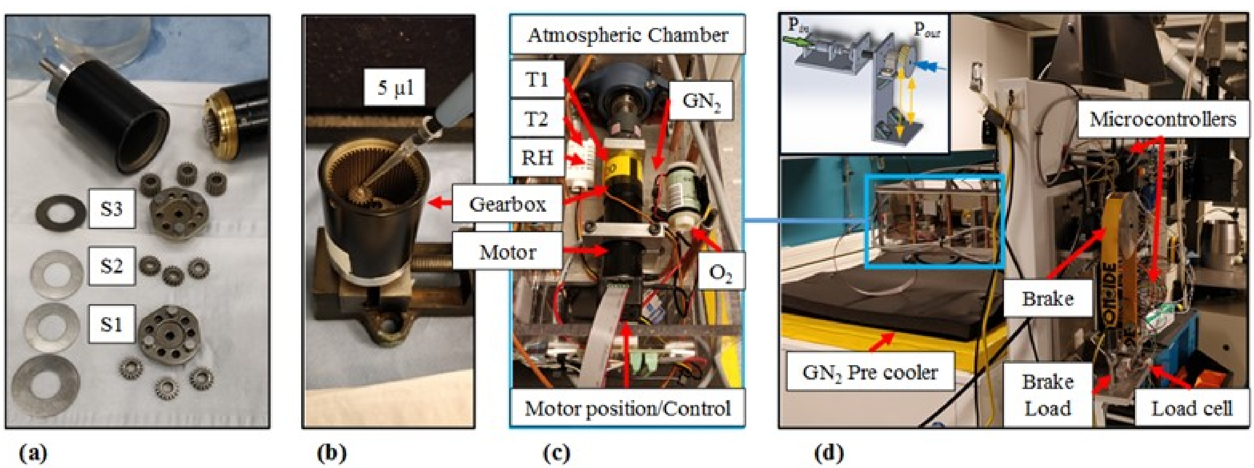

Figure 1. (a) Dissasembled 3-stage planetary gearbox. (b) Procedure of applying lubricant to planet gear. (c) Atmospheric chamber enclosing actuator and sensors. (d) Overview of Geared Actuator Test Rig.

GATR test conditions
The GATR experiments are started at –20°C in >99% N_2 and run for a duration of 1h at 8050 rpm at a nominal braking torque of 0.8 Nm. Every 5 minutes, the motor is stopped for 10 seconds before ramping the speed back up to 8050 rpm at 1000 rpm/s. This test is repeated twice with the second repetition at 1.0 Nm braking torque, giving a total of 1.5 M input pinion revolutions (~30 000 at output). In total, five actuator units are evaluated: 2 units are lubricated with MAC, 2 with P-SiSO, and 1 with PFPE. Units number 2 are used for repetition of the first test with MAC and P-SiSO.

Post-test damage analysis
After subjecting the gearbox to 1.5 million input cycles, post test damage analysis is performed in three scales; (1) surface macro scale by optical inspection and digital microscopy, (2) surface micro scale by 3D surface profilometry and scanning electron microscopy with electron dispersive x-ray spectroscopy (SEM-EDS), and finally (3) sub-surface microscale analysis by x-ray micro tomography (XMT). After initial inspection of MAC and P-SiSO lubricated gears, two gear teeth are cut out of a Stage 3 (S3) planet gear using electric spark erosion to be further analyzed. The thin tribofilms are analyzed by SEM in low voltage high contrast detector mode (vCD) at 3 kV, using a Magellan 400 FEG-SEM (FEI Company, Eindhoven, The Netherlands). EDS was performed using an X-Max 80 mm^2 X-ray detector (Oxford Instruments, Abingdon, UK) operated at 3-5 kV, which is just enough to detect the elements C, O, Fe, and Si. Finally the gear teeth are scanned with XMT using a Zeiss Xradia 510 Versa (Carl Zeiss X-ray Microscopy, Pleasanton, CA, USA), with a resolution of 4 µm per voxel (volume pixel). Tiff stacking and a Canny method edge-detection algorithm was employed to quantify sub surface damage from XMT data.

Results and Discussion

Results I – Efficiency and Temperature
The actuator efficiency and temperature over a 1 hour test cycle is shown in Figure 1. Between the three lubricants, a clear trend in both efficiency and temperatures can be distinguished with efficiency ranking of P-SiSO>MAC>PFPE. As expected, efficiency and temperature are inversely correlated, with high efficiency corresponding to low temperature increase and vice versa. This corresponds to previous model scale tribotests where variants of P-SiSO has been shown to reduce friction and wear compared to neat PFPEs as well as formulated lubricants [5], [6].

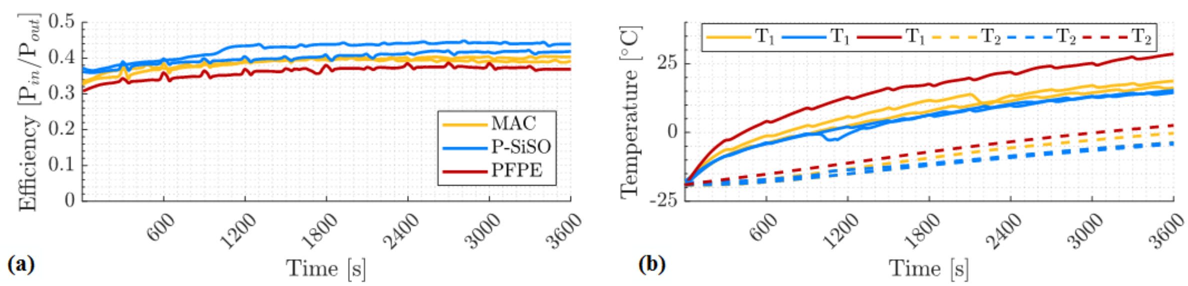

Figure 2. (a) Measured efficiency of actuator setup when lubricated with MAC, P-SiSO, and PFPE respectively. lubricants. (b) Gearbox housing temperature (T_1) and chamber interior temperature (T_2) over 1 h test (500 000 input revolutions). As expected, efficiency is inversely related to increasing gear house temperature (T_2).

Results II – Macroscale surface inspection
The gearboxes were disassembled and inspected after 3h of test. PFPE showed evidence of heavy wear, with large amount of wear particles. Therefore we focused on MAC and P-SiSO. Inspection of MAC Stage 3, Figure 3(a), revealed dark particles and discolouring of the separator disc (B). EDS analysis confirmed a layer rich in carbon, indicating indicating decomposition of the hydrocarbon lubricant. Microscopy image of the MAC driven gear show a clear wear pattern, with particle build up towards the root. Inspection of P-SiSO Stage 3, Figure 3(b), did not show any obvious sign of degradation., but microscopy images show a

blue and purple region above and below the pitch line of the driven gear, indicating tribofilm formation. Regardless of MAC or P-SiSO, the driven gear showed more signs of wear than the driver gear.

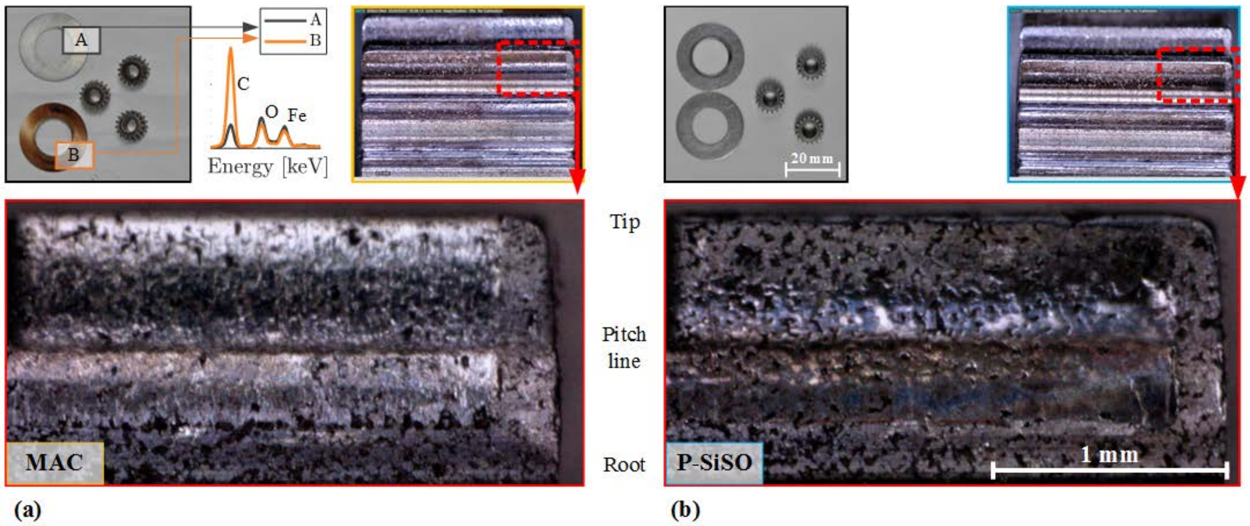

Figure 3. Inspection of Stage 3 components. (a) MAC show visible lubricant degradation (confirmed by EDS) on stage 3 separator disc. Microscope image indicate wear above and below pitch line. (b) No sign of lubricant degradation in P-SiSO case. Worn area color shift indicates formation of boundary film.

<u>Results III – Surface micro scale and elemental analysis</u>

Figure 4 displays the surface topography of the driven gears seen in Figure 3, together with a topography map of an unworn tooth. In the case of MAC and P-SiSO, the measurement was made after cutting the teeth so that the full size of the gear could be scanned. Despite this, very little data is recorded below the pitch line. Above the pitch line, the MAC shows an elliptic region that covers about 1/3 of the gear, whereas the case of P-SiSO is limited to the edges of the gear. The MAC topography has likely also been severly worn below the pitch line, but the large height differential over the gear profile makes it difficult to capture the effect on surface roughness in this area.

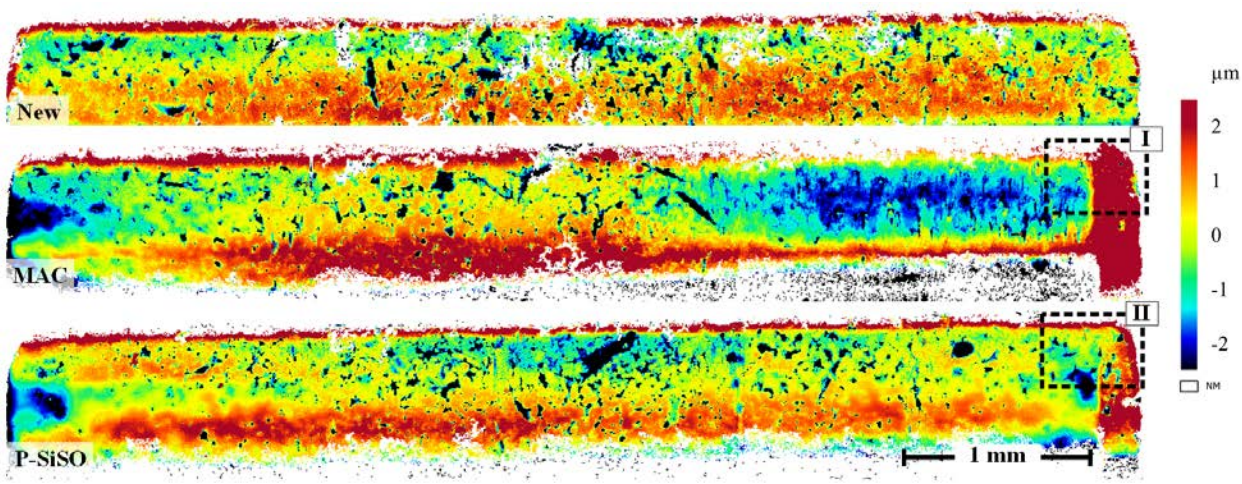

Figure 4.Gear surfaces as seen by 3d profilometry in 10x objective. Wear patterns of MAC and P-SiSO are compared with New (unworn) surface. Dedendum is mostly out of range because of gear involute profile, but tendency of high wear by MACis seen. Regions I and II are selected for 50x objective evaluation.

Increasing the magnification provides insight to the active wear and damage mechanisms. In Figure 5(a) the MAC surface show signs of scuffing, with adhered particles and abrasive marks. In contrast, Figure 5(b) show a surface where the original sintered pores remain, but the load bearing patches between pores are very smooth. A surface roughness profile (avoiding pores) reveal that the surface parameters are significantly improved compared to the unworn reference, as well as the MAC or PFPE (not shown).

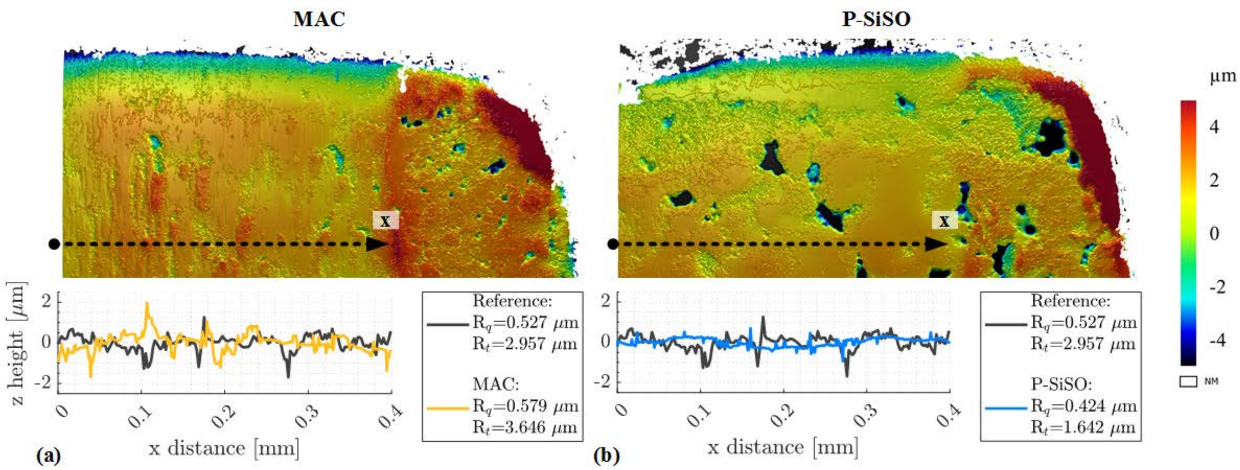

Figure 5. Regions I-II of MAC and P-SiSO respectively, with roughness profiles and parameters along x profile. (a) MAC surface show evidence of partial seizures (scuffing). (b) P-SiSO produce smooth contact patches and retains the porous structure of the unworn sintered material.

Region II (P-SiSO) was analyzed by SEM-EDS investigate the lubrication mechanism. A patchy tribofilm is clearly visible when using the low voltage high current detector (vCD). However, the EDS analysis could not confirm the presence of silicate. When comparing to a SRV model tribotest, shown in the top right inset of Figure 6(b), it is clear that the tribofilms have a similar visible appearance. The EDS spectra also show similarities in terms of Fe/O/C proportions, but Si is lacking in the analyzed gear surface. Possibly, the gear tribofilm is too thin to be detectable by EDS, even at the low accelerating voltages of 3-5 keV used.

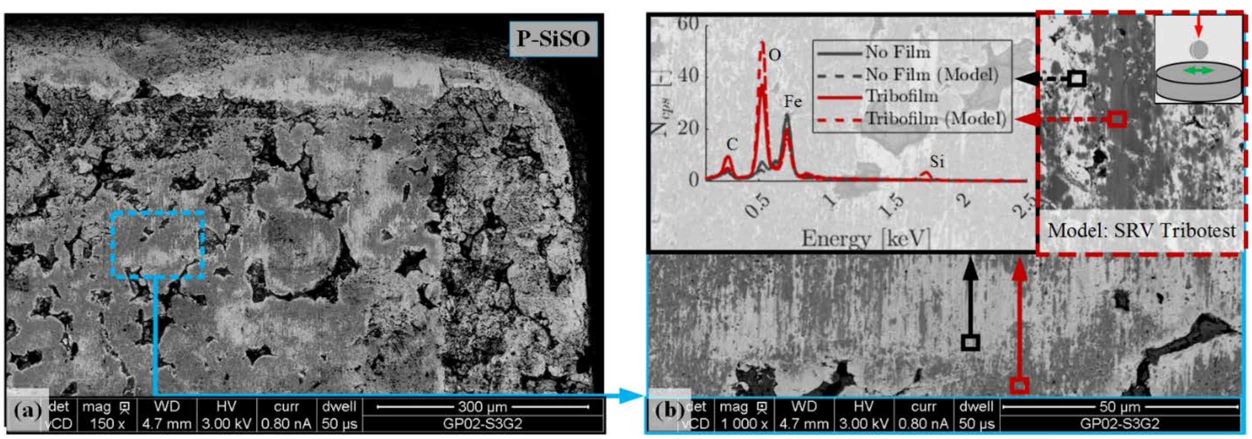

Figure 6. SEM-EDS analysis of P-SiSO driven gear Region II. (a) Overview indicate gear surface is covered with tribofilm. (b) Gear tribofilm compared to P-SiSO tribofilm generated in ball-on-flat SRV tribotest.

<u>Results IV – Sub-surface micro scale analysis</u>

The analysis is limited to ~1 mm^3 of the gear teeth located at the x-coordinate corresponding to the center of the worn region in Figure 4. The colormap show the frequency of detected edges in the y-z plane. The gray scale refers to the density of the material; bright regions correspond to metal (dense) and dark regions to pores (air). Addendum (i) and dedendum (ii) regions on the driven (N) and driver (R) side of the gear are chosen for comparison. Figure 7(a) show adhered metal, confirming scuffing at region (N_{ii}). Interstingly, in the same region there are also sub-surface edges detected, which indicates risk of sub-surface cracks. The subset images show possible crack formations at x-coordinate $X_{1\text{–}4}$. Figure 7(b) shows significantly less activity in the colormap produced by the edge detection algorithm, indicating lower risk of sub-surface cracks. High friction is usually detrimental to sub-surface cracking. In starved lubrication conditions, the efficiency improvement of P-SiSO over MAC is likely attributed to surface friction, and therefore it is reasonable to assume less sub-surface cracking.

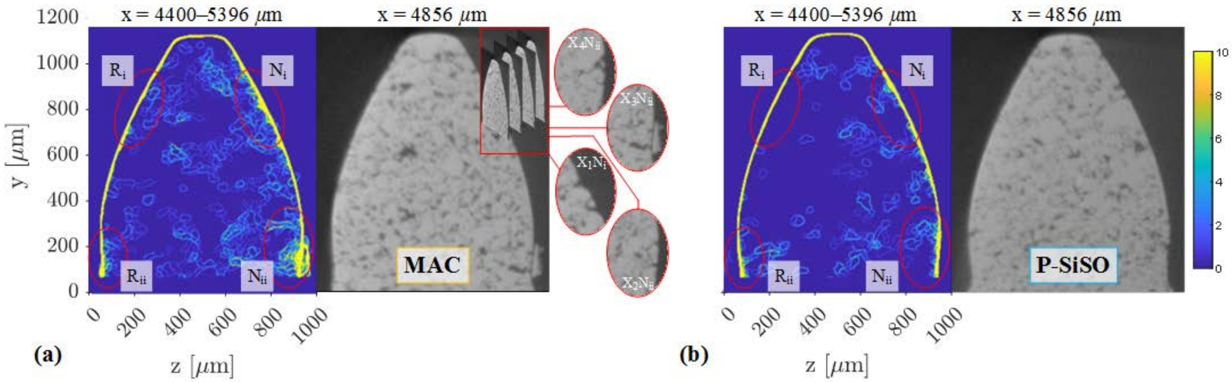

Figure 7. XMT analysis indicates potential sub-surface cracking. Driven side dedendum (N_{ii}) is critical region. (a) MAC show severe scuffing with large particles adhered at N_{ii}, and evidence of subsurface cracks in the same region (b) P-SiSO show less overall detected edges, and no evidence of scuffing.

Conclusions

- A hydrocarbon mimicking ionic liquid combined with multiply alkylated cyclopentane (P-SiSO) was evaluated in geared actuators under starved lubrication conditions in N_2 atmosphere.
- P-SiSO significantly reduced surface and sub-surface damage, while increasing gearbox efficiency.
- P-SiSO covered the gear with a thin tribofilm, comparison with model tribotest indicates silicate.
- Surface roughness was clearly improved by P-SiSO, which likely improves (micro-)EHL conditions.
- XMT is well suited for damage analysis of sintered metal gears. The porous structure is susceptible to sub-surface cracking, which can be distinguished by XMT over the entire gear volume.

Acknowledgements

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