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Achieving Macroscale Liquid Superlubricity Using Lubricant Mixtures of Glycerol and Propanediol

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Abstract

Friction and wear are ubiquitous in moving mechanical systems, and achieving vanishing friction and wear could significantly improve the energy efficiency and extend the service life of mechanical components. In this paper, two types of propanediol, viz. 1,3-propanediol (13-PD) and 1,2-propanediol (12-PD), have been selected to be mixed with glycerol for superlubricity performance. The results show that the lubricant mixture of 13-PD and glycerol (13-PD/glycerol) is effective in providing superlow friction (COF < 0.01) for steel tribopairs under an ambient atmosphere environment with little surface damage caused. However, 12-PD that exhibits the same chemical formula as 13-PD except for the configuration of hydroxyl groups is ineffective in superlubricity achievement. Experimental and molecular dynamics simulation results show that the superlow friction realized by the lubricant mixture of glycerol and 13-PD is related to the enhanced intermolecular hydrogenbonding interaction and the formation of adsorbed molecular layers. The intermolecular layers affects the passivating efficiency of the interactions between opposite surfaces. Compared with 12-PD, the hydroxyl groups of 13-PD are more exposed for intermolecular interaction. This paper could help provide a guideline to the design of novel lubricants for superlubricating performance and push the development of liquid superlubricity for future engineering applications.

Graphical Abstract



Keywords Macroscale liquid superlubricity · Glycerol · Propanediol · Hydrogen-bonding

Extended author information available on the last page of the article

1 Introduction

Superlubricity with vanishing friction is promising to solve energy dissipation and prevent premature working components failure induced by friction and wear. It is estimated that 23% of the world's total energy is consumed by tribological contacts, and the implementation of advanced surface treatment techniques, novel base materials, and innovative lubricants could potentially reduce the energy loss by 40% [1]. To achieve this goal, researchers have paid lots of effort to reveal the mystery behind the friction phenomena, and several factors, including contact adhesion, interfacial bonding, viscous dissipation, and microstructure evolution, have been interpreted to be the main causes [2–7]. Precisely tunning these factors sheds light on achieving controlling friction or even vanishing friction.

The atomistic origin of friction under various dimensionality was researched by Hirano in the 1990s, vanishing friction was predicted to be achievable at high dimensionality when two conditions were met: the adiabatic motion of atoms and the phenomena of energy recurrence [8-10]. Furthermore, he found that these two conditions could be satisfied using two clean flat crystalline surfaces that engage an incommensurate orientation, where forces acting on each atom could cancel out [10, 11]. Up to now, this hypothesis has been experimentally demonstrated within molybdenum disulfide sheets, graphene sheets, carbon nanotubes, and some heterogeneous structures in micro/nanoscale under a vacuum atmosphere [12–16]. However, in real applications, the reactive species of oxygen and water in the air and the intrinsic defects of materials could enhance the interfacial interaction and cut off the stable sliding area, leading to the non-adiabatic motion of atoms and causing continual energy dissipation. Hence, achieving vanishing friction directly in macroscale using solid materials is of great challenge.

Liquid lubricated systems could partially or even totally separate the solid contacts by generating thin pressurized



Fig. 1 Atomic structure of glycerol, 1,3-propanediol, and 1,2-propanediol molecules employed in this work

lubricant films, remarkably alleviating the severity of friction. The overall friction for a liquid lubricated system comes mainly from two sources: the viscous dissipation of lubricant films and the adhesive interaction between the opposite asperities [17–19]. The former could be controlled through viscosity modification, and the latter can be minimized by the adsorption of molecular layers of lubricant molecules. Recently, hydration lubrication has emerged as a promising strategy for macroscale liquid superlubricity, where water molecules are kept by charges surrounding ions or polar molecules [20–25]. The generated hydration layers could not only maintain flexibility like liquids but remain integrity under pressure. Furthermore, both water and polar molecules could attach to the friction surface to minimize the interfacial bonding. One drawback of this approach is that it requires hundreds of seconds long wearing-in before transiting to the vanishing friction state, during which serious materials loss could be caused [26]. Though adding nanoparticles in lubricants could reduce the wear to an extent, it does not fundamentally solve the issue and the long wearingin process still exists [27].

In our study, as displayed in Fig. 1, glycerol is employed as the base liquid lubricant to be mixed with two types of propanediol, viz. 1,3-propanediol and 1,2-propanediol, pursuing stable and robust superlubrication for steel tribopairs. Compared with glycerol (viscosity = $875 \text{ mPa} \cdot \text{s}$), the viscosity of the two propanediol is only about 48 mPa·s, which is desirable for preparing shearable lubricant mixtures. Furthermore, propanediol is non-corrosive, less volatile, and unharmful to humans, thus it is an ideal candidate for realizing superlow friction. In this paper, the rheological properties of lubricants and their tribological performances have been tested. Furthermore, molecular dynamics simulation has also been conducted to explain the behaviors of lubricant molecules at the atomic scale. The results in this work could help provide a guideline to the future tailored design of lubricants with superlubricity performance.

2 Materials and Methods

2.1 Experimental Details

Glycerol (purity = 97%), 1,3-propanediol (13-PD, purity = 99%), and 1,2-propanediol (12-PD, purity = 99.5%) were purchased from Alfa Aesar. Lubricant mixtures of propanediol and glycerol (propanediol/glycerol) were prepared by mixing propanediol with glycerol at various propanediol/ glycerol weight ratios, viz., 0.2, 0.4, 0.6, and 0.8. Further ultrasonication process was carried out to mix the mixtures uniformly. To be specific, the liquid mixture was processed in an ultrasonic water bath for 30 min, during which the ultrasonic frequency and power were set at 40 kHz and 300 W, respectively. For simplicity, the prepared mixtures were labeled according to propanediol used and the specific propanediol/glycerol weight ratio: 13-PD/glycerol=0.2, 0.4, 0.6, and 0.8; 12-PD/glycerol=0.2, 0.4, 0.6, and 0.8. Steel disk and ball made of AISI 52,100 steel were used as the tribopairs. The ball diameter is 9.5 mm and its surface roughness R_q is about 20 nm. The diameter and the height of the disk are 30 mm and 5 mm, respectively, and its surface roughness R_q was polished to be about 20 nm.

The kinetic viscosity of lubricants was measured by Cannon–Fenske Routine Viscometer, and the surrounding temperature was controlled to be 25 °C by CANNON CT-2000 Extended Range Constant Temperature Bath. The lubricant density was further experimentally determined, and the corresponding dynamic viscosity was obtained by multiplying the kinetic viscosity of lubricants with their densities.

Tribotests were carried out on CETR UMT-2 ball-on-disk tribometer. The wear track diameter and the rotation speed were maintained at 12 mm and 159.23 rpm, respectively, corresponding to a linear speed of 0.1 m/s. The applied load was adjusted from 4 to 7 N, with the calculated Hertz contact pressure of 723–871 MPa. The testing duration was 30 min. Repeat tests were conducted, which showed great reproducibility. After the test, tribospairs were rinsed with methanol to remove the residual lubricant. Furthermore, during the test, the temperature was about 25 °C, and the relative humidity was about 23%. The surface morphology of steel surfaces was characterized by Laser Confocal Microscope (Bruker).

The deposit formed on the ball surface was analyzed by Horiba Raman, where a 473 nm laser source was employed.

2.2 Computation Details

Molecular dynamics (MD) simulation has been conducted on LAMMPS, which is a widely used large-scale atomically massively parallel simulator [28]. A Reactive force field (ReaxFF) that had been validated for hydrocarbon and iron – oxyhydroxide systems was employed [29, 30]. The open-source visualization tool OVITO was used for all the visualizations [31]. The structure of MD simulation models in this work was created by an open-source software Packmol [32]. The MD simulations consisted of three parts, the first was to study the intermolecular interaction between glycerol and two types of propanediol, the second was the sliding simulation, and the last was to study the interaction between lubricant molecules with Fe_3O_4 surface. All the simulation results and the corresponding error bar shown in the paper were obtained from the last 5 ps of simulation.

The intermolecular interaction between glycerol and propanediol molecules was first simulated, with the setup shown in Fig. 2a, where a number of glycerol and propanediol molecules were randomly mixed. Specifically, the number of glycerol molecules was kept at 150, and the number of propanediol molecules was 72, which corresponded to the propanediol/glycerol weight ratio of 0.4. The simulation box was then relaxed at 300 K for 100 ps. After the relaxation process, the number of hydrogen bonds formed



Fig.2 a The intermolecular hydrogen-bonding interaction model for lubricant mixtures; **b** Computation setup configuration for sliding simulation, with 13-PD/glycerol=0.4 was displayed here as an exam-

ple; **c** Interaction analysis model for pure lubricant molecules with Fe_3O_4 surface, where the number of lubricant molecules was kept at 5 to minimize the intramolecular interaction effect

between glycerol and propanediol was analyzed. As for the hydrogen-bonding definition, the cutoff distance between the hydrogen-bond donor and acceptor was defined to be less than 3.5 Å, and the corresponding angle was below 30° [33].

The sliding simulation aimed to reveal the configuration of lubricant molecules between the two sliding slabs during the sliding process. To be specific, as displayed in Fig. 2b, each Fe₃O₄ slab consisted of three parts: outer rigid layer, middle thermostatic layer, and inner non-thermostatic layer. All the atoms within the rigid layer were frozen without any movements or oscillations, while the velocities of atoms within middle thermostatic layers were allowed to be adjusted to couple with the set temperature. As for the nonthermostatic layers, atoms were allowed to move or oscillate freely without any external restrictions. During the sliding simulation, 1 GPa pressure was applied to the top rigid layer to push it down until the separation distance of the two slabs came to a relatively steady value. Then, the system was allowed to relax for 100 ps, with the two thermostatic layers coupled at 300 K. Finally, a shear velocity V_x of 10 m/s was applied to the top rigid layer, and the sliding motion lasted for another 800 ps. Furthermore, for the sliding simulation system, the number of glycerol molecules was kept at 100, and the number of propanediol molecules was 48, corresponding to the propanediol/glycerol weight ratio of 0.4.

The interaction between lubricant molecules with Fe_3O_4 surface was also analyzed. Figure 2c displays the configuration setup for this simulation process. Specifically, five lubricant molecules of glycerol, 13-PD, and 12-PD were placed 5 Å beyond the iron oxide surface in a vacuum slab. The whole system was relaxed at 300 K and 1 atm for 100 ps, which was long enough for the whole system to reach an



Fig. 3 Average COF for a 13-PD/glycerol and b 12-PD/glycerol lubrication systems with various propanediol/glycerol weight ratios. c Friction curve vs. time for several selected lubricant mixtures

equilibrium state, with the lubricant molecules adsorbed to the substrate surface in the end. Then, the lubricant molecules were removed above from the adsorbed substrate surface for a distance of 10 Å, which was far enough to neglect the interaction between the lubricant molecules and the Fe₃O₄ slab surface. The variation of energy within this removal process corresponded to the total adsorption energy, which was then divided by the number of molecules simulated and the average adsorption energy for each molecule could be obtained. The adsorption energy of lubricant molecules is useful to analyze the robustness and the efficiency of lubricant molecules to form lubricious adsorbed molecular layers.

3 Results

The friction performance of the prepared lubricant mixtures of 13-PD/glycerol and 12-PD/glycerol with various propanediol/glycerol weight ratios has been first evaluated at 4 N and 0.1 m/s on a ball-on-disk rotating tribometer at ambient atmosphere environment.

Figure 3a–c display the average COF evolution vs. the propanediol/glycerol weight ratio for the prepared diol/glycerol accomplishes superlubricity at 13-PD/glycerol=0.4, with a minimum COF of 0.007. Comparatively, as seen in Fig. 3b, the average COF values for 12-PD/glycerol are all beyond the superlubricity regime, ranging from 0.013 to 0.018. Figure 3c illustrates some of the selected friction traces. Obviously, 13-PD/glycerol=0.4 achieves superlubrication within

420 s. In the case of 12-PD/glycerol=0.4, about 1410 s is consumed before transiting to the vanishing friction state. Thus, it could conclude that 13-PD is superior to 12-PD in enabling superlubric behavior.

To further assess the wear performance, steel balls after the test have been cleaned to remove the residual lubricants and then analyzed under a microscope, and the results are presented in Fig. 4a. Clearly, little surface damage is caused to steel balls for all the tests, with only some black deposits stacked around the wear area. The Raman spectra shown in Fig. 4b display the characteristics at 1358 cm⁻¹ and 1538 cm⁻¹, which have been widely interpreted to be carbonaceous substances. These adsorbed carbonaceous substances could passivate the steel surfaces, hindering the adhesive contact between tribopairs and improving the lubrication condition.

Figure 5a displays the viscosity of pure glycerol and two types of propanediol. Pure glycerol presents an ultrahigh viscosity of 874 mPa·s, which is more than one order of magnitude than the two propanediol (~48 mPa·s). Figure 5b presents the viscosity of the prepared propanediol/glycerol lubricant mixtures, which presents a significant decrease with the propanediol/glycerol weight ratio. A lower viscosity means reduced shear resistance within lubricant layers, desirable for reducing the energy dissipation caused by viscous flow. Apparently, the viscosity-reducing capability of 13-PD is higher than 12-PD.

Although less viscous lubricants are considered more fuel economy, it also risks bringing about more asperity contacts, causing high friction and wear. The theoretical minimum lubricant film thickness of the tribopairs has been evaluated



Fig. 4 a Optical micrographs and b Raman characteristics of black deposits of steel ball after the friction tests at 4 N and 0.1 m/s in pure glycerol, 13-PD/glycerol=0.4, and 12-PD/glycerol=0.4



Fig. 5 a Viscosity of pure glycerol, 13-PD, and 12-PD; b Viscosity of the prepared propanediol/glycerol lubrication systems versus propanediol/glycerol weight ratio; c Calculated theoretical minimum lubri-

cant film thickness and **d** the corresponding lambda ratio. The viscosity presented was measured at 25 $^{\circ}$ C

via the widely used Hamrock–Dowson equation (as displayed in Appendix A1) [32–35]. Figure 5c illustrates the plots of the calculated theoretical minimum lubricant film thickness. Apparently, the lubricant film decreases with the diol/glycerol weight ratio. At the same diol/glycerol weight ratio, 13-PD/glycerol exhibits lower lubricant film thickness than 12-PD/glycerol. Lambda ratio has been further calculated to evaluate the magnitude of asperity contact situation, and tribopairs with lambda ratio below 1 is believed to be in mixed/boundary lubrication state where relatively severe asperity interaction exists. As shown in Fig. 5d, the lambda ratio drops below 1 at 13-PD/glycerol=0.8 for 13-PD/glycerol. In the case of 12-PD/glycerol lubrication systems, the lambda ratios are always beyond 1. Furthermore, the surface roughness of the disk and ball has also been measured after the test and the corresponding lambda ratio has also been calculated. Specifically, as for 13-PD/glycerol = 0.4 at 4 N and 0.1 m/s, the Rq for ball and disk reduces to 19 nm and 16 nm, respectively, and the lambda ratio is calculated to be increased from 1.24 to 1.42. As for 13-PD/glycerol = 0.6, the lambda ratio increased from 1.03 to 1.20. This phenomenon demonstrates the occurrence of the tribo-polishing effect within the sliding test, which could further contribute to the achievement of superlow friction. Thus, the observed superlubric phenomenon in this paper is obtained in the mixed hydrodynamic lubrication regime where an effective elasto-hydrodynamic lubrication film could be formed.

Limited load-bearing capability is a big concern for the future industrial applications of macroscale liquid superlubricity. Here, we have further explored the tribological



Fig. 6 Friction performance of the selected lubricant mixtures (pure glycerol, 13-PD/glycerol=0.4, and 12-PD/glycerol=0.4) at various loads: **a** 5 N, **b** 6 N, and **c** 7 N. **d** Corresponding average COF evolution with the applied load

performance of 13-PD/glycerol = 0.4 and 12-PD/glycerol = 0.4 at high loads of 5–7 N, with the results are presented in Fig. 6. It is clear that 13-PD/glycerol = 0.4 always present reduced COF than pure glycerol, while 12-PD/glycerol = 0.4 does not see any friction improvement. Figure 6d displays the calculated average COF at various loads. The maximum load for 13-PD/glycerol = 0.4 to maintain the superlubrication state is 5 N, with the corresponding contact pressure of 769.11 MPa. When the load is further increased to 6–7 N with the corresponding contact pressure of 817.30–860.39 MPa, the average COF for 13-PD/glycerol = 0.4 is still as low as 0.012-0.016.

Considering the configuration difference of hydroxyl groups for 13-PD and 12-PD molecules, it could anticipate that the difference in their working performance should be related to the intermolecular interaction. It has been reported

that the ultrahigh viscosity of glycerol is due to its strong intermolecular H-bonding interaction between glycerol molecules that forms a three-dimensional hydrogen-bonding network [36]. Propanediol molecules are miscible with glycerol by forming intermolecular H-bonds. The dissolved propanediol molecules could embed in the self-associated threedimensional structure of glycerol molecules, as depicted in Fig. 7a, b, working as structure breaker to hinder the strong glycerol-glycerol intermolecular interaction [37]. As the strong glycerol-glycerol interaction has been effectively weakened, hence the propanediol/glycerol mixtures exhibit lower viscosity.

To analyze the intermolecular interaction of lubricant molecules, MD models have been established by mixing a certain number of glycerol and propanediol molecules; then, the whole system has been subjected to relaxation process.



Fig.7 Schematic illustration of the intermolecular H-bonding interaction between **a** glycerol and 13-PD as well as **b** glycerol and 12-PD; **c** The number of intermolecular hydrogen bonds (H-bonds)

formed between glycerol and propanediol for 13-PD/glycerol=0.4 and 12-PD/glycerol=0.4



Fig. 8 The number count of lubricant molecules between two iron oxide surfaces after 800 ps of sliding simulation: **a** 13-PD/glycerol = 0.4 and **b** 12-PD/glycerol = 0.4

The number of intermolecular H-bonding formed between propanediol and glycerol molecules has been counted, as displayed in Fig. 7c. Overall, 13-PD could reduce the glycerol-glycerol intermolecular H-bonds more efficiently than 12-PD. The superior intermolecular H-bonding capability of 13-PD compared to 12-PD is due to the configuration of two hydroxyl groups. In the case of 13-PD, the two hydroxyl groups are located at the two-carbon chain ends, which are more exposed for intermolecular interaction than in 12-PD molecules, whose two hydroxyl groups display a vicinal configuration [38–42]. In conclusion, the superior intermolecular H-bonding interaction capability of what 13-PD presents endows it with enhanced rheology modifying ability.

For a lubricant mixture, its friction performance is also affected by the distribution of lubricant molecules at the interface. MD sliding simulation has been carried out to help understand the distribution of lubricant molecules across the interface during the sliding test, and the results are illustrated in Fig. 8. In the case of 13-PD/glycerol = 0.4, as shown in Fig. 8a, it can see that13-PD molecules tend to gather around the upper slab. In contrast, as seen in Fig. 8b, lubricant molecules of 12-PD/glycerol = 0.4 present an even distribution. The enrichment of 1,3-propanediol molecules near the sliding surfaces for 13-PD/glycerol=0.4 lubrication system could reduce the viscous drag of lubricant films to friction surfaces, beneficial to facilitating the relative sliding and reducing the shear resistance. In the meanwhile, the remaining part with reduced 1,3-propanediol molecules would be slightly more viscous that keeps the tribopairs apart more efficiently. Thus, the desirable distribution of lubricant molecules for 13-PD/glycerol is helpful to the achievement of superlow friction.

Asperity interaction is always regarded as the main cause of high COF and wear. In our work, lubricant molecules of glycerol and diols abundant with hydroxyl groups have been employed, which are capable of adsorbing to steel surface to alleviate the severity of steel-to-steel interaction. The specific interaction strength of lubricant molecules with iron oxide surface has been evaluated by MD simulation, with the results shown in Fig. 9a. Evidently, glycerol with three hydroxyls groups exhibits the highest average adsorption strength of 93 kJ/mol, and the adsorption strength of 13-PD (~64 kJ/mol) is slightly higher than that for 12-PD (~62 kJ/ mol). Figure 9b-d illustrate the specific orientation of molecules on the iron oxide surface, and it can see that glycerol and 13-PD could always interact with iron oxide surface via their exposed hydroxyl groups, either in a flat or inclined direction. However, 12-PD could possibly attach to substrate surfaces using its methyl group, which is unstable and can be easily removed under shear. Thus, 13-PD is more desirable than 12-PD for creating robust molecular layers to alleviate the steel-to-steel interaction.

In conclusion, 13-PD could provide robust superlubricity for steel tribopairs, while 12-PD is ineffective for this purpose. The difference arises mainly from two causes: one is their intermolecular H-bonding capability with glycerol molecules, and the other is the interaction ability with steel surfaces. The intermolecular H-bonding capability shows the efficiency of the propanediol molecules to break the strong self-association network of glycerol molecules, which could modify the rheological property of the lubricant and make it much less viscous. Compared with 12-PD, 13-PD is more prone to forming intermolecular hydrogen bonds due to its more exposed hydroxyl groups. Thus, as shown in Fig. 5b,

Fig. 9 a Adsorption strength calculation of pure glycerol, 13-PD, and 12-PD with iron oxide surface. The orientation of specific alcohol lubricant molecules on substrate surface: **b** glycerol, **c** 13-PD, and **d** 12-PD



13-PD is more effective than 12-PD in viscosity reduction. Similarly, the more exposed hydroxyl groups of 13-PD are also beneficial to the enhanced interaction with steel surface, hence 13-PD exhibits higher adsorption energy than 12-PD, and the higher adsorption strength means enhanced prevention to direct metal-to-metal contacts at asperity contacts. The interaction ability of lubricant molecules with substrate surface is related to the robustness of molecular layers formed on friction surfaces and its effectiveness in passivating steel-to-steel interaction without being sheared off easily. The tribo-smoothing effect could also decrease the asperity interaction between tribopairs. Furthermore, the MD sliding simulation indicates that the 13-PD molecules within the 13-PD/glycerol = 0.4 lubrication system are prone to residing near the friction surfaces, which could further reduce the friction drag and facilitate the relative sliding.

4 Conclusions

In summary, vanishing friction, viz. superlubricity state, has been enabled by mixing 13-PD with glycerol, whereas 12-PD is ineffective for this purpose. Experiments and molecular dynamics simulations have been conducted to interpret the mystery. Some major conclusions are listed below:

- Propanediol could embed in the self-associated threedimensional structure of glycerol molecules by intermolecular H-bonding interaction, working as structure breaker to hinder the strong glycerol-glycerol interaction, which hence makes the lubricant mixture less viscous and much easier to shear;
- (2) 0.13-PD with hydroxyl groups at the ends of carbon chain presents enhanced intermolecular H-bonding interaction with glycerol than that for 12-PD with hydroxyl groups presenting a vicinal configuration;
- (3) Sliding simulation shows that 13-PD molecules are prone to accumulating near the sliding surfaces, beneficial to reducing the viscous drag to the sliding surface; while the remaining part with fewer propanediol molecules would be more viscous to separate the tribopairs. Comparatively, 12-PD presents a uniform distribution;
- (4) The more exposed configuration of hydroxyl groups for 13-PD molecules could enable them to interact with steel surfaces more effectively, forming robust adsorbed lubricant molecular layers. Comparatively, 12-PD with hydroxyl groups in a vicinal configuration could form weak and unstable adsorption points, which could be easily removed by shear.

Appendix

Estimation of Theoretical Lubricant Film Thickness Between Tribopairs

Hamrock-Dowson equation (shown in Eq. 1) is used to estimate the minimum theoretical lubricant film thickness formed between the tribopairs:

$$\frac{h}{R'} = 2.69 \left(\frac{U\eta_o}{E'R'}\right)^{0.67} \left(\alpha^* E'\right)^{0.53} \left(\frac{F}{E'R'}\right)^{-0.067} \left(1 - 0.61e^{-0.74k}\right)$$
(1)

where *R'* refers to the reduced radius of tribopairs, *U* is the entrainment velocity of two sliding surfaces, η_0 is the dynamic viscosity of lubricant used, *E'* the effective modulus of tribomaterials, *F* the applied normal load, α^* the pressure-viscosity index of lubricant, and *k* the ellipticity parameter (= 1 in this case). α^* is reported to be 6 GPa⁻¹ for glycerol, and 5 GPa⁻¹ for propanediol [43]. The α^* for prepared diol/glycerol mixtures is estimated by formula $\alpha^* = \alpha_1^* f_1 + \alpha_1^* f_2$, where α_1^* and α_2^* refer to the respective pressure-viscosity index of pure glycerol and diol, and f_1 and f_2 are their corresponding weight concentrations. Lambda ratio λ is calculated by Eq. (2):

$$\lambda = \frac{h}{\sqrt{\sigma_1^2 + \sigma_2^2}} \tag{2}$$

where σ_1 and σ_2 refer to the surface roughness of the counter surfaces.

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Declarations

Conflict of interest The authors declare that there is no competing financial interest for this work.

Ethical approval The authors declare that the manuscript is original, and has been submitted solely to this journal and is not published, in press, or submitted elsewhere.

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