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水潤滑下におけるシリカナノ粒子担持による Si-DLC 膜の摩擦特性向上

Low-frictional properties of Si-DLC films by silica nanoparticle support under water lubrication

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1. Introduction

The global world faces an increasing threat from energy depletion and the continuous rise of greenhouse gas emissions. However, petroleum remains the primary energy source, significantly impacting the environment. In response, stricter environmental regulations have driven industries toward sustainable and eco-friendly technologies [1].

One such environmentally friendly technology in Tribology is water lubrication, which utilizes water as a lubricant to achieve friction reduction under boundary lubrication conditions. In particular, Si_3N_4 self-mated and SiC self-mated tribopairs have demonstrated ultra-low friction coefficients below 0.01 [2]. This phenomenon has been attributed to the formation of Si-O rich compounds or layers through tribochemical reactions between ceramics and water, which are believed to be responsible for the ultra-low friction behavior [3].

However, most mechanical components involving physical contact are not made of ceramics, and the high production costs of ceramics present a major challenge to their widespread industrial adoption. Therefore, there is an urgent need to extend water-lubricated tribological technologies to more cost-effective and manufacturable engineering materials.

In this study, we propose an approach to achieving ceramic-like low friction in steel by incorporating silica nanoparticles (SiO_2) into the sliding interface as a means of enriching Si-O bonding. To enhance the adhesion of silica nanoparticles, Si-doped diamond-like carbon (Si-DLC) was employed as a binder layer, which is expected to form strong chemical bonds with SiO_2. The tribological performance of Si-DLC coatings loaded with silica nanoparticles was evaluated under water boundary lubrication using a ball-on-disk tribometer. Additionally, we investigated the effect of atmospheric plasma treatment prior to testing on the water lubrication properties of Si-DLC films containing silica nanoparticles.

2. Experimental Methods

Si-DLC (a-C:H:Si) coatings with approximately 8 wt.% Si content were prepared using the plasma-enhanced chemical vapor deposition (PECVD) method. The Si content was measured using scanning electron microscopy with energy-dispersive X-ray spectroscopy (EDS), where the Si and C compositions were normalized to a total of 100%. The substrates used were high-carbon chromium-bearing steel (SUJ2).

To achieve low-friction performance, silica nanoparticles with an average particle size of 9 nm were deposited onto the surface of the Si-DLC coating. The deposition process involved spreading the nanoparticles uniformly over the coating surface, followed by atmospheric plasma treatment to enhance the binding stability between the nanoparticles and the surface.

A schematic of the ball-on-disk tribometer setup is shown in Fig. 1. Si3N4 balls were used as counter bodies. During the test, deionized water was continuously supplied near the contact area to maintain an immersed condition. The test parameters included a sliding distance of 1880 m and applied loads of 10 N. Tribological tests were conducted on two types of specimens: one treated with atmospheric plasma for 90 s prior to testing and one without plasma treatment.

After the tribological tests, optical microscopy was used to observe wear tracks, and laser confocal microscopy was employed to analyze surface roughness.

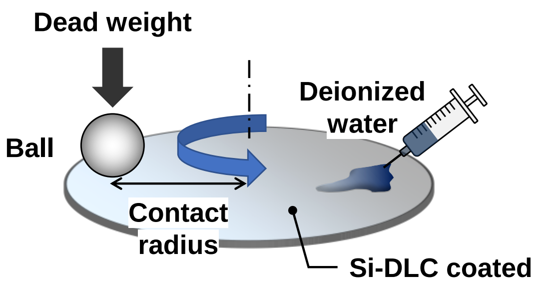

Fig. 1 Schematic configuration of Pin-on-Disk tribometer.

3. Results and discussion

Fig. 2 presents the friction coefficient as a function of sliding distance for Si-DLC under water lubrication, with and without silica nanoparticles. The friction coefficient of Si-DLC in water lubrication ranged between 0.06 and 0.08, consistent with reported values for Si-DLC coatings under similar conditions [4]. However, silica nanoparticles led to a significant friction reduction, particularly during the initial 400 m of sliding, where the coefficient dropped to approximately 0.02. This suggests that silica nanoparticles contribute to an initial low-friction regime, likely by acting as lubricating nanostructures or facilitating the formation of a tribofilm. However, beyond 400 m of sliding, the friction coefficient gradually increased over the test duration.

In contrast, when the Si-DLC surface was treated with atmospheric plasma immediately before testing, the low friction coefficient of 0.02 was maintained throughout the entire 2000 m sliding distance (Fig. 3). This indicates that plasma treatment plays a crucial role in stabilizing the friction-reducing effect of silica nanoparticles, possibly by enhancing their adhesion to the surface or modifying the surface chemistry to favor long-term water-based lubrication.

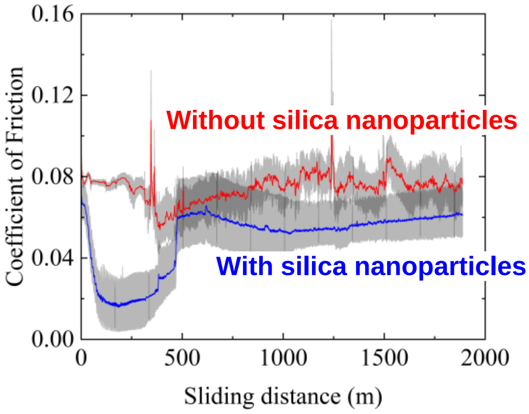

Fig. 2 Effect of silica nanoparticles on the friction coefficients of Si-DLC coatings in water lubrication.

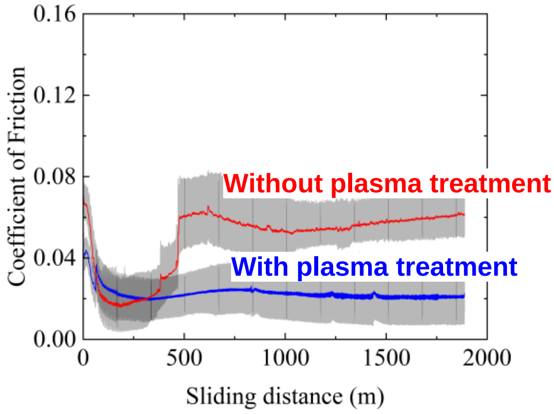

Fig. 3 Effect of plasma treatment on the friction coefficients of Si-DLC coatings in water lubrication.

4. Conclusion

In this study, we investigated the effect of atmospheric plasma treatment prior to testing on the water lubrication properties of Si-DLC coatings loaded with silica nanoparticles. The conclusions drawn from this study are as follows:

- Regardless of whether atmospheric plasma treatment was applied before friction testing, the minimum friction coefficient for Si-DLC coatings with silica nanoparticles was approximately 0.02.
- Specimens subjected to atmospheric plasma treatment prior to testing maintained a lower friction coefficient throughout the entire sliding test compared to those without plasma treatment.

These findings highlight the potential of combining plasma treatment with nanoparticle-based lubrication strategies for achieving long-lasting low-friction performance in aqueous environments.

References

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