# COMPARISONS OF DEPLETION AND REPLENISHMENT CHARACTERISTICS OF MOLECULARLY THIN PFPE LUBRICANT COATED ON MAGNETIC DISKS UNDER NON-UV- AND UV-IRRADIATED CONDITIONS

（紫外線照射条件と非照射条件における分子潤滑膜の減耗・修復特性の比較）

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## INTRODUCTION

In hard disk drives, to ensure the long-term reliability and durability of head-disk interfaces, liquid polymeric films of perfluoropolyether (PFPE) are applied to the disk surface at a thickness of 1-2 nm. To protect the disk surface from solid contact with the magnetic head, such molecularly thin films must firmly adhere to the disk surface so that no film rupture occurs in sliding during contact (retention function); these films must also spread quickly to replenish depleted areas if film rupture does occur (replenishment function). Ultraviolet (UV) ray irradiation on the lubricated surface is an effective way to enhance the retention function, but it may lead to a reduced replenishment function. To optimize the UV irradiation, it is essential to quantitatively clarify the effects of UV irradiation on the durability of lubricant film against in-contact sliding. In this paper, we performed sliding tests on a disk surface lubricated with monolayer PFPE lubricant under the non-UV- and UV-irradiated conditions. In the tests, lubricant films were gradually depleted by repeated sliding of a precisely finished glass ball, and changes in the cross section of the lubricant film were measured over the elapsed time. From the comparisons, UV irradiation was found to permit a higher durability owing to smaller depletion without losing the recovery performance.

## EXPERIMENTAL MATERIALS

Magnetic disks three inches in diameter were used as the lubricated sliding surface. These disks are comprised of a glass substrate, an underlayer, a magnetic layer, and a diamond-like carbon (DLC) overcoat. The DLC overcoat was fabricated using chemical vapor deposition, and then it received nitriding treatment. Surface roughness measured Ra= 0.35 nm. The liquid

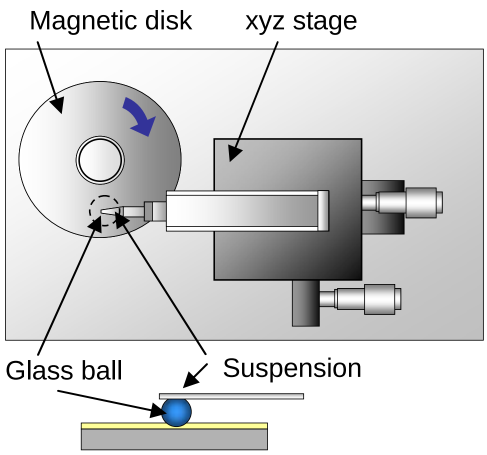



Fig. 1 Experimental apparatus.

lubricant used was commercially available Fomblin PFPE (AM3001, Solvay Solexis, Inc.) possessing UV-reactive end groups. AM3001 was fractionated to give a number average molecular weight of 4000 g/mol.

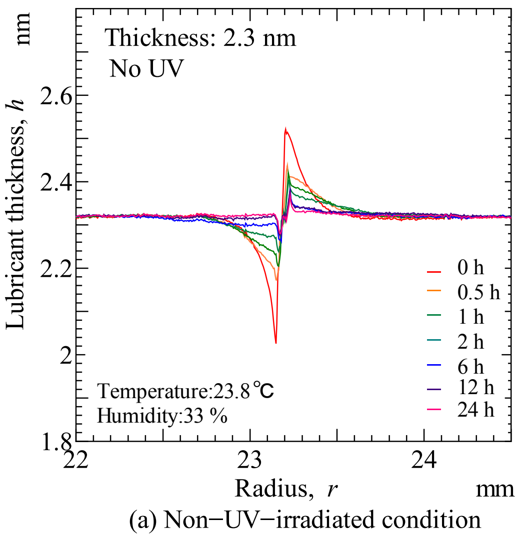
The PFPE films were dip-coated onto the disk surfaces by briefly immersing the disk in a solution of PFPE in HFE-7200 (3M Corp.) and then withdrawing it from the solution. In this work, the solution concentration was fixed at 0.2 wt%, and the withdrawal speed was set at 1.0 mm/s to form a film thickness of nearly 2 nm, i.e., monolayer thickness.

Thirty minutes after film deposition, the lubricated disk was treated inside a nitrogen-purged chamber by UV irradiation. A dielectric barrier discharge excimer lamp (USER20-172B, Ushio Inc.) that provided UV radiation at 172 nm was used as the light source [1]. The distance between the lamp house and the disk was set to 9 mm and UV irradiation time to 60 s. The irradiation time was selected as the time when bonding of lubricant molecules with a DLC surface tended to saturate with additional irradiation time.

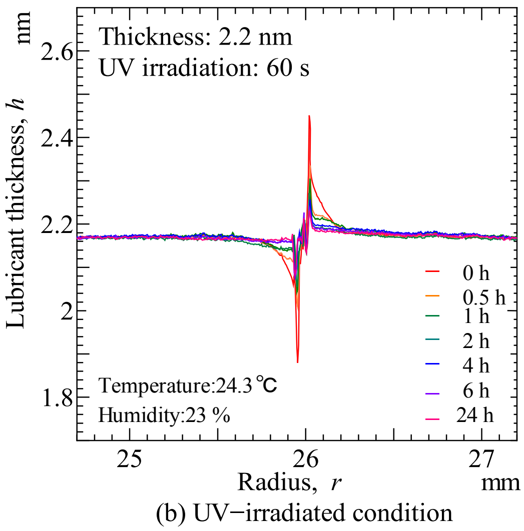
## EXPERIMENTAL APPARATUS AND PROCEDURES

To deplete the lubricant film coated on a magnetic disk, the pin-on-disk sliding tester shown in Fig. 1 was used [2]. A magnetic disk was mounted on the head of a spindle supported by an air bearing and rotated with a belt. A sliding pin was glued to the end of a spring suspension. The sliding pin was made of bolosilicate glass (BK7) having a diameter of 1.5 mm, which was originally for optical lens use (Chuo-Seiki). Its surface roughness measured Ra=1.0 nm and Rmax=9.5 nm using atomic force microscopy (AFM). Having an Rmax value larger than the lubricant film thickness permitted some peaks of roughness to penetrate the film, and with unlubricated sliding, these roughness peaks would cause DLC wear. As described in the next section, the wear trace of the DLC surface was considered much narrower than that of the lubricant film, so DLC wear did not significantly affect the results. Gentle and mild sliding conditions were selected to avoid severely damaging the layering structure of the lubricant molecules. These conditions were a sliding velocity of 0.63 m/s (20-mm radius of sliding zone and 300-rpm disk rotation), a loading force of 98 mN, and disk turns of 30,000 passes.

The average profile over one cycle is used in this study. Sliding tests for the UV-irradiated case were performed after one day from the UV irradiation and those for the non-UV-irradiated case after one day from the dip coating. The recorded elapsed time began from the end of the sliding test. All experiments were performed in a clean room with an air conditioner.



(a) Non−UV−irradiated condition



(b) UV−irradiated condition

Fig. 2 Lubricant profile changes after depletion test.

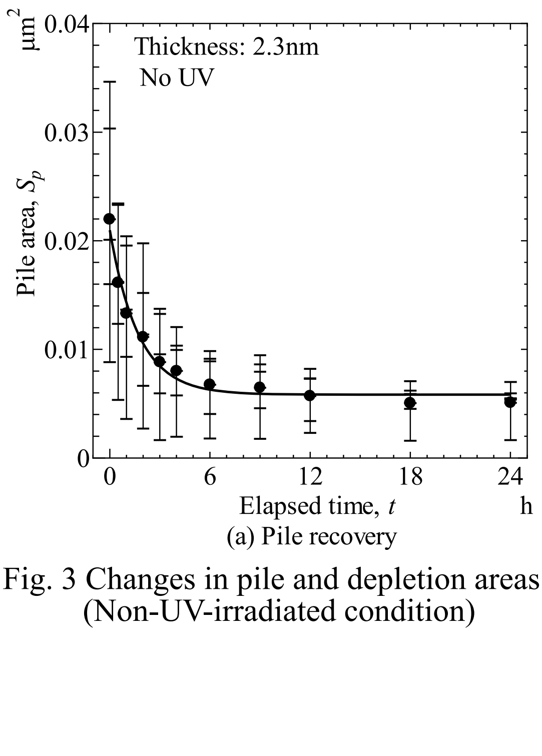
## DEPLETION AND REPLENISHMENT OF LUBRICANT FILMS

A typical example of the cross section of lubricant film after the sliding test for the non-UV-irradiated case is shown in Fig. 2(a). A valley where the lubricant was depleted and a peak where the lubricant was piled-up are observed. The bottom of the sliding ball sits just around the transition of the peak and valley. It is evident that the valley and peak became lower while maintaining nearly symmetrical change, which indicates that reflow from the peak to the valley restored the sliding trace, and the initial flat surface nearly recovered after an elapsed time of 24 hours.

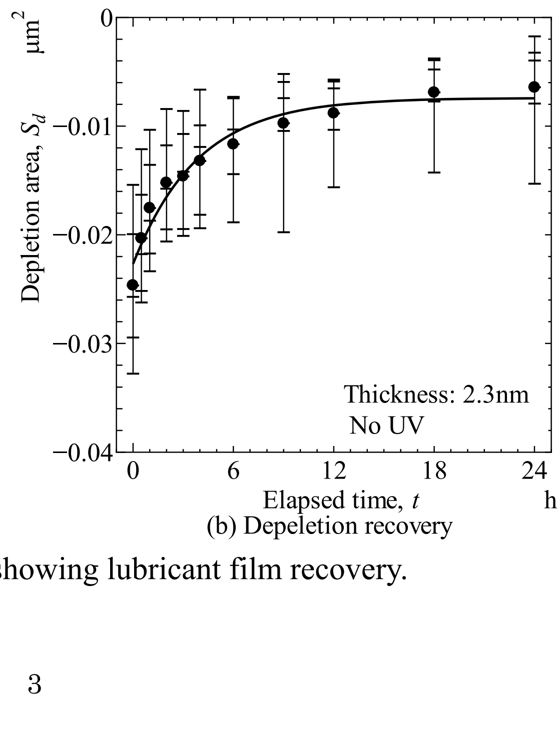
Figure 2(b) exemplifies the same cross-section changes except for the UV-irradiated case. The peak and valley are observed in the same manner as the non-UV-irradiated case. A special feature is observed in the fact that the peak and valley became steeper and narrower, indicating that the areas of the peak and valley were also decreased. This demonstrates that sliding-induced depletion was substantially decreased by UV irradiation. It was found that wide variation in the experimental results was inevitable caused by local variations in contact conditions. To yield enough meaningful results, we performed the same experiment five times using different disks and averaged the results.

## COMPARISONS OF DEPLETION AND REPLENISHMENT CHARACTERISTICS

Since sliding traces were observed in a pair of the peak and valley as shown in Fig. 2, we calculated the area of the lubricant cross section separately for the peak and valley, and named them pile area and depletion area, respectively. As for the non-UV-irradiated case, the changes in the pile and depletion areas are shown in Fig. 3 (a) and (b), respectively. The hyphen symbol indicates each value for five experiments, showing the scattering range at a specified elapsed time, and the solid circle designates the averaged value of five data. The solid line denotes the fitted curve of the averaged values as will be discussed in detail later. The initial values of the pile and the depletion are found to range from 0.009 to 0.035 μm$^2$, indicating fairy large scattering. The averaged values are 0.022 μm$^2$ for the pile and 0.025 μm$^2$ for the depletion, which are nearly equal to each other. From the solid line decreasing monotonously, it can be inferred that the data averaged over the five experiments permitted us to obtain representative recovery characteristics.



(a) Pile recovery



(b) Depeletion recovery

Fig. 3 Changes in pile and depletion areas showing lubricant film recovery. (Non-UV-irradiated condition)

As for UV-irradiated case, the changes in the pile and depletion areas are shown in Fig. 4 (a) and (b), respectively. Their initial values are found to range from 0.011 to 0.022 μm$^2$, indicating that the scattering range was much smaller than in the non-UV-irradiated case. The averaged values for the pile and the depletion equal each other at 0.015 μm$^2$, which is nearly 2/3 times smaller than that for the non-UV-irradiated case. This reveals that UV irradiation allows increasing durability, as can be predicted from the fact that UV-irradiation serves to increase the bonding of lubricant molecules to the DLC surface.

Using the averaged recovery characteristics, let us calculate recovery speed and recovery rate for the pile and depletion, respectively. Curve fitting was applied to the averaged values to obtain time dependent features. Since the recovery process can be treated as a relaxation process, we selected the following reference function:

$$S(t) = (S_0 - S_\infty) \times \exp(-t/\tau) + S_\infty \quad (1)$$

where $S_0$, $S_\infty$, $t$, and $\tau$ mean the initial area, the saturated area, the elapsed time, and the time constant, respectively. Note that a short time constant means a fast recovery speed. Let us define the recovery rate as $\alpha = (S_0 - S_\infty)/S_0$, then equation (1) is rewritten as:

$$S(t) = S_0\{1 - \alpha[1 - \exp(-t/\tau)]\} \quad (2)$$

Fitting parameters obtained for the four cases are listed in Table 1. From this table, it is found that the time constant was longer for the depletion than that for the pile. The reason for this can be attributed to the fact that the molecules involved in the pile can move not only toward the valley, but also toward the opposite site, that is, to the undamaged original lubricated surface. In other words, the entire molecules involved in the pile are not to be used to recover the valley. Comparing the time constants, we know that UV irradiation elongated the time constant by 1.2 times for the depletion and 1.7 times for the pile. This indicates that the reduction in the recovery speed is fairly slight for the depletion, whereas it is noticeable for the pile. However, the time constant for the pile is much shorter than that of the depletion, therefore it might not lead to meaningful disadvantages.

From the comparisons of the recovery rate, it is found that UV irradiation did not noticeably affect the depletion recovery rate. This is attributed to the fact that a fresh surface appeared on the wall of the valley, and this feature might apply nearly equally for both non-UV- and UV-irradiated cases. On the other hand, the pile recovery rate decreased somewhat with UV irradiation. This might be originated from the fact that the reflow toward the undamaged surface became more difficult with UV irradiation. This is in good accordance with the fact that UV-irradiation serves to considerably decrease the surface energy of the lubricant surface, which serves to suppress the reflowing from the pile.

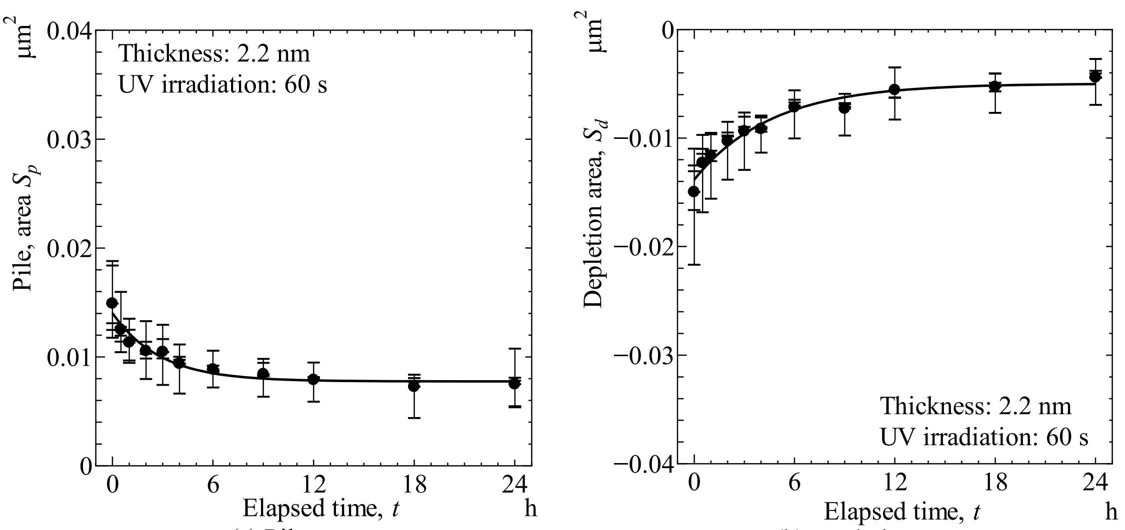



Fig. 4 Changes in pile and depletion areas showing lubricant film recovery. (UV-irradiated condition)

## CONCLUSION

To quantitatively evaluate UV irradiation effects on the sliding durability of lubricant film at monolayer thickness, we performed the pin-on-disk sliding test on non-UV- and UV-irradiated PFPE lubricant films coated on magnetic disks covered with a DLC layer. The lubricant films were gradually depleted using a glass ball with an optically smooth surface. Experiments were performed repeatedly five times using different disks to yield enough meaningful results from the experimental scattering data. The cross sections of the lubricant films subject to in-contact sliding were measured over the elapsed time using an optical surface analyzer at sub-nanometer resolution. After the sliding test, a peak and a valley where lubricant was piled up and removed, respectively, were observed adjacent to each other with the sliding track at their boundary. Over the elapsed time, the peak and valley became smaller, indicating that the initial film thickness tended to recover. The cross-section areas of the peak and valley, which are called the pile area and depletion area, were calculated to compare the non-UV-irradiated and UV-irradiated cases. The comparisons revealed that the pile and depletion areas for the UV-irradiated case decreased to two thirds of the non-UV-irradiated case indicating that UV irradiation was effective for decreasing lubricant wear. Finally, we applied a curve fitting method based on a relaxation model to obtain the time constant and the recovery rate for characterizing the recovery process. Comparing the time constants and recovery rates between the non-UV- and UV-irradiated cases, it was found that UV irradiation hardly affected the depletion recovery process but did somewhat decelerate the pile recovery rate. From these comparisons, it was clarified that UV-irradiation has the advantage of decreased lubricant depletion while maintaining the depletion recovery performance, thus providing higher durability at the head-disk interface.

## REFERENCES

[1] Zhang, H., Mitsuya, Y., Fukuoka, N., Imamura, M., Fukuzawa, K., *Self-organized Patterning of Molecularly Thin Liquid Polymer Films Utilizing Molecular Flow Induced by Ultraviolet Irradiation*, Applied Physics Letters, 90 (2007), 123119.

[2] Y. Mitsuya, H. Zhang, J. Ohgi, K. Fukuzawa, *Experimental Comparisons of Spreading and Replenishment Flows of Molecularly Thin Lubricant Films Coated on Magnetic Disks*, IEEE Transaction on Magnectics, 44(2008), 3641-3644.

| | | $S_0$ (μm$^2$) | $\tau$ (h) | $\alpha$ |
|---|---|---|---|---|
| Non UV | Pile | 0.021 | 1.7 | 0.72 |
| | Depletion | -0.023 | 3.9 | 0.67 |
| With UV | Pile | 0.014 | 2.8 | 0.45 |
| | Depletion | -0.014 | 4.6 | 0.64 |

Table 1 Fitting parameters for the time-dependent changes of pile and depletion areas