Enhanced Photo-Thermal Stability of Modified PFPE Lubricants Under Laser Beam Exposure

M. Gauvin[1], H. Zheng[1], B. Suen[1], J. Lee[2], H. J. Kang[2], and F. E. Talke[1]

[1]Center for Magnetic Recording Research, University of California San Diego, La Jolla, CA 92093 USA
[2]Department of Polymer Science and Engineering, Dankook University, 126, Jukjeon-dong, Suji-gu, Yongin-si, Gyeonggi-do 448-701, Korea

The photo-thermal stability and tribological properties of Zdol lubricant, modified by substituting the OH groups with benzophenone, were investigated under laser beam exposure. The change of reflectance of the modified Zdol lubricant films induced by laser beam exposure was measured using a surface reflectance analyzer (SRA). The friction force of modified Zdol lubricant films was measured at the interface between a slider and a disk on a spin stand. Modified Zdol films show less reflectance change than pure Zdol. The photo-thermal stability under laser beam exposure increases with an increase of the substitution ratio. Reflectance change occurs due to depletion of the lubricant and/or modification of the lubricant optical properties under laser beam exposure. Unlike pure Zdol, the normalized friction force of modified Zdol remains constant under laser beam exposure. Modified Zdol lubricants are potential disk lubricants for heat-assisted magnetic recording applications.

Index Terms—**Hard disk drive, heat-assisted magnetic recording, laser beam exposure, lubricant depletion and thin lubricant film.**

I. Introduction

HEAT-ASSISTED magnetic recording (HAMR) is a promising approach to increase the areal storage density of magnetic recording disk drives beyond 1 Tbit/in^2 [1], [2]. HAMR systems use a laser beam to locally heat the magnetic medium above its Curie temperature, thereby reducing the coercivity of the medium. As the temperature starts to drop, the coercivity of the magnetic medium is still low enough for allowing the write field to magnetize the medium. The medium magnetization becomes "frozen" as the temperature decreases to room temperature [3]. During writing, the magnetic medium is exposed to a highly focused radiative field delivered by a near field transducer. Radiative energy is transfered and dissipated in the magnetic medium causing a temperature increase not only of the magnetic medium, but also of the lubricant film and the carbon overcoat on top of the magnetic medium. The temperature increase raises concerns about the stability and performance of lubricants used in HAMR applications. Therefore, an understanding of the effect of radiation and temperature on the performance of HAMR-type lubricants is of importance.

Perfluoropolyethers (PFPEs) are widely used in hard disk drives due to their good tribological properties at ambient conditions, and in particular, due to their chemical inertness, low surface tension, low partial pressure and low coefficient of friction. Li *et al.* [4] reported that the weight-loss of Z-type PFPE lubricants occurs in a temperature range between 200°C and 500°C, depending on the molecular weight and end groups. One of the PFPE lubricants that has been widely used in the past is Zdol [5]. The weight-loss mechanism of Zdol, at elevated temperature, is driven by evaporation for low molecular weight Zdols and thermal oxidative decomposition for high molecular weight Zdols, respectively [4]. Degradation of Zdol is initiated by oxidation of the hydroxyl end-groups. Degradation due to molecular chain breakage and/or depletion of PFPE lubricant films have been observed under laser exposure [6]–[8]. Lubricants adapted to HAMR systems should maintain their good tribological characteristics and resist degradation when exposed to elevated temperatures and high radiative energy from the laser light source in thermally assisted magnetic recording.

Thermal and photo-stability of PFPE lubricants may be enhanced by functionalizing the end groups or by increasing the molecular weight [7]. Lee *et al.* have reduced photo-degradation of Zdol by using pentafluorobenzophenone as a UV-stabilizer (UVS) additive [9]. They found that the Zdol/UVS mixture undergoes phase separation over time due to chemical incompatibility of the different compounds. In this work, a different approach was investigated by functionalizing the hydroxyl end groups of Zdol using a UVS compound. In particular, Zdol2000 hydroxyl end groups were partially replaced by benzophenone, an effective UV-stabilizer. Substitution of the hydroxyl end groups can be controlled by adjustment of the reaction conditions. In this paper, we study the weight loss of the modified lubricants under high temperatures. In addition, we investigate the degradation and frictional properties of modified Zdol lubricant films with different substitution ratio, under laser beam exposure.

II. Experimental Setup

A. Lubricant Synthesis and Deposition

Fig. 1(a) shows the molecular structure of 4-(bromomethyl)benzophenone. Fig. 1(b) shows a schematic of the Zdol modification reaction process which will be described in more details elsewhere. First, hydroxyl end groups in Zdol are alkoxylated with a catalyst (sodium) to improve reactivity. Then UV-stabilizer moieties (UVS: benzophenone) react with

Manuscript received December 19, 2010; revised March 28, 2011; accepted March 31, 2011. Date of current version June 24, 2011. Corresponding author: F. E. Talke (e-mail: ftalke@ucsd.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TMAG.2011.2140362

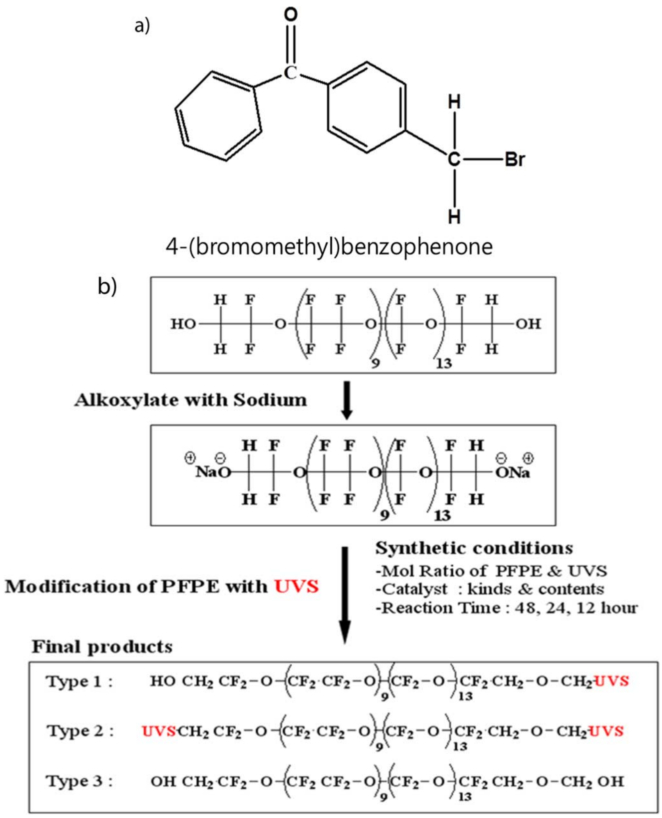

Fig. 1. a) Molecular structure of 4-(bromomethyl)benzophenone used to modify Zdol2000. b) Reaction process of Zdol2000 modification.

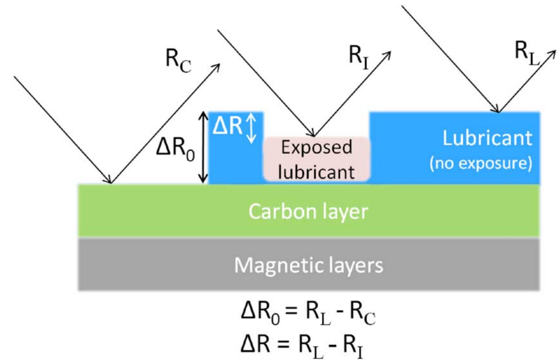

Fig. 2. Cross-section of a multilayer system composed of a lubricant film, a carbon layer and magnetic layers under laser beam exposure. ΔR_0 corresponds to the initial lubricant film thickness without laser beam exposure. Under assumption of constant optical index, ΔR corresponds to the change of lubricant film thickness under laser beam exposure.

alkoxylated PFPE to substitute the ONa end groups. Hydroxyl end groups of Zdol can be replaced either by one UVS group (type 1), two UVS groups (type 2) or none (type 3). Depending on reaction conditions, such as reaction time and molar ratio of Zdol2000/catalyst/UVS, reaction products are characterized by a different average substitution ratio. Final reaction products were analyzed by ^{1}H nuclear magnetic resonance (NMR), using a 200 MHz Varian Zemine 2000 instrument, to determine the average substitution ratio accounting for a mixture of the three types of modified Zdol. Thermal stability of bulk lubricants was characterized by thermogravimetric analysis (TGA) using a Mettler TG15 analyzer. Weight loss due to thermal degradation in air was determined through dynamic scanning up to 700°C with a scanning rate of 20°C/min.

Degradation and frictional properties of Zdol2000 lubricant with 22%, 48%, and 72% of substitution ratio were investigated and compared with pure Zdol lubricant under identical laser beam exposure conditions. Modified Zdol lubricants are referred to as $\mathrm{HAMR}_{22\%}$, $\mathrm{HAMR}_{48\%}$, and $\mathrm{HAMR}_{72\%}$, respectively. Pure lubricants were diluted with HFE 7100 solvent to obtain 0.1 weight % solutions and deposited on glass disks of 65 mm diameter, sputtered with a perpendicular magnetic media and a wear protective carbon overcoat. Lubricant films with thickness in the range of 1.5 nm to 2 nm were deposited at different drain speeds using a dip-coater [10].

B. Optical Surface Properties

The reflectance signal of the disk surface partially coated with a lubricant film was characterized using a surface reflectance analyzer (SRA) [11]–[13]. The SRA is an optical measurement system using reflected polarized light to determine the optical properties and the thickness of thin films on a substrate. Spatially resolved s-polarized (R_s), p-polarized (R_p) light and phase contrast (R_{ph}) intensities are simultaneously monitored with a resolution better than of 0.01%, and mapped over the sample surface.

A theoretical model based on the light interaction with thin films was used to interpret the reflected polarized light properties in terms of modification of the thickness and the optical constants of the lubricant layer on the disk. The optical model takes into account the difference of reflectance between lubricated (R^L) and unlubricated (R^C) surfaces, defined as $\Delta R_0 = R^L - R^C$ (cf. Fig. 2). Theoretical values of s-polarized (R_s), p-polarized (R_p) light and phase contrast (R_{ph}) intensities were calculated based on the formalism described in Azzam's book [14].

The Fresnel coefficients were evaluated assuming a beam reflected at the interface between air and a planar, multi-layer system composed of a lubricant film, a carbon film and a magnetic layer. R_p and R_s are defined with respect to the complex p-polarized (r_p) and s-polarized (r_s) reflectivities given by

$$r_p = \sqrt{R_p} e^{i\delta_p} \tag{1}$$
$$r_s = \sqrt{R_s} e^{i\delta_s} \tag{2}$$

where δ_p and δ_s are the phase parameters of the p-polarized and s-polarized complex reflectivities, respectively. R_{ph} is the total reflectivity intensity modulated by the phase shift between s- and p-polarized components, given by

$$R_{ph} = \frac{1}{2}\left(\pm\sqrt{R_p R_s} cos(\delta) + (R_p + R_s)/2\right) \tag{3}$$

where R_p, R_s are intensities of the p-polarized and s-polarized components, respectively, and δ is an ellipsometric parameter corresponding to the phase shift $\delta_p - \delta_s$, between p- and s-polarization of the reflected light from the sample surface. R_{ph}, as defined in (3), shows higher sensitivity to the lubricant film compared to R_s and R_p intensities [13]. Therefore, the phase contrast intensity signal was considered to quantify the effect

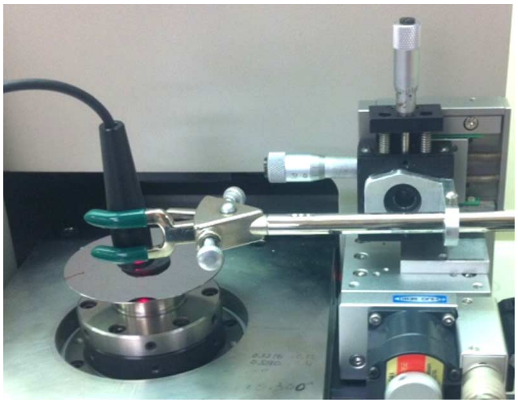

Fig. 3. Experimental setup for studying the effect of laser light irradiation on the thickness variation of a modified Zdol thin film.

of laser exposure on the lubricant film reflectance. A positive sign was adopted in (3) as the convention in the following discussion. Isotropic properties were assumed for each layer. Optical constants published for cobalt by Johnson and Christy [15] were used to describe the magnetic layer. For the carbon overcoat, we have used optical constants from Chia *et al.* [16]. Considering the variation in reflectance ΔR_0 from the lubricated surface relative to the unlubricated disk (cf. Fig. 2) allows to limit errors due to uncertainties in the properties of the magnetic layer and the carbon overcoat. Given similar thickness and optical parameters, the values of ΔR_0 were consistent with the results reported by Klein and Vurens [13]. The change of reflectance (ΔR) between non-irradiated (R^L) and irradiated (R^I) lubricated surfaces $(\Delta R = R^L - R^I)$, as shown in Fig. 2, is monitored as a function of exposure time and average output beam power. To compare the effect of laser irradiation among the different lubricant films, we consider the ratio $\Delta R/\Delta R_0$, where ΔR_0 refers to the initial reflectance difference between the lubricated and the unlubricated surfaces, without laser beam exposure.

C. Experimental Setup

In our study, a 660 nm laser diode was used to investigate the effect of laser light irradiation on the thickness of a modified PFPE film on a hard disk surface. The experimental setup shown in Fig. 3, consists of a spindle, a hard disk and the laser diode mounted on a linear motor. The whole setup is part of a surface reflectance analyzer commercially available for measuring film thicknesses of lubricated surfaces. The laser beam is pulsed at 3 MHz and the pulse duration is ≈200 ns. The beam is focused on the sample surface with a spot size of about 1 μm using a magnifying optical camera. The laser is moved along 5 mm tracks in the radial direction of the disk, at a linear speed of 0.5 mm/s while the disk is kept stationary. The laser is translated parallel to the disk surface using a linear actuator to ensure a constant laser spot size on the disk surface. The average optical output power was varied between 20 and 107 mW as measured by a power meter (Lasercheck, Coherent).

D. Friction Experiments

Prior to friction tests, lubricated disks were thermally treated at 90°C, for 24 h to achieve lubricant bonding to the carbon overcoat. The friction force at the interface between the rotating

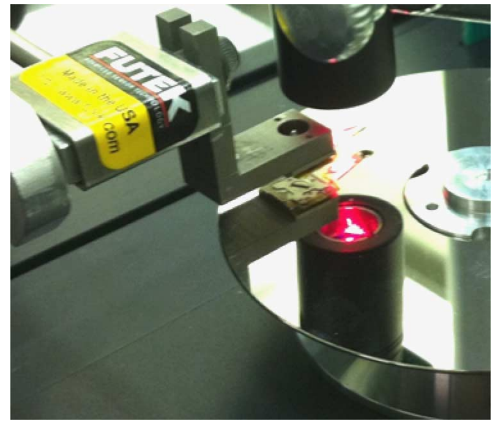

Fig. 4. Drag-test for studying the effect of laser light irradiation on friction force of a modified Zdol thin film.

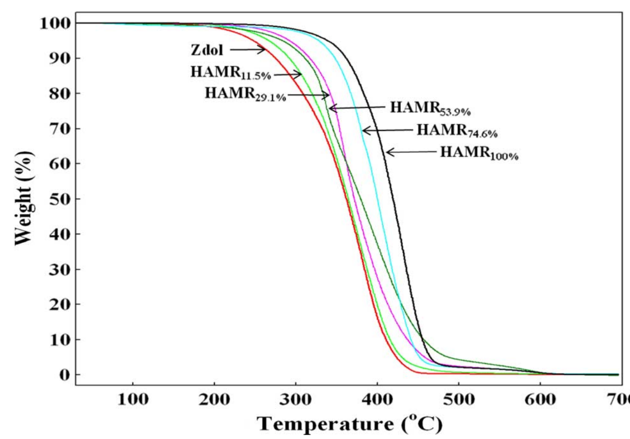

Fig. 5. Thermal stability of modified Zdol lubricants for different substitution ratios.

disk and the slider attached to the suspension was measured with a load cell, as shown in Fig. 4. The slider was positioned with a skew angle of zero degree relatively to the circumferential direction of the disk. The friction force was sampled at 12.8 kHz and the normal load was fixed at 25 mN. Drag tests were performed at a constant speed of 1 m/s. We compare the friction force obtained with modified Zdol lubricants to that of pure Zdol by normalizing the friction force of each lubricant to the friction force of Zdol2000 measured prior to laser beam exposure. To investigate the effect of laser exposure on the friction of the different lubricants, the normalized friction force prior to laser beam exposure was compared with the friction force obtained in the same "wear" track after laser beam exposure. The laser beam was directed at the wear track on the disk through a hole in the suspension (cf. Fig. 4).

III. Results and Discussions

A. Thermal Stability of Bulk Lubricants

Fig. 5 shows thermogravimetric results of modified Zdol bulk lubricants for different substitution ratios. We observe that the thermal stability of bulk modified Zdol lubricant increases as the substitution ratio increases, i.e., the thermal stability of modified Zdol improves with a higher content of benzophenone.

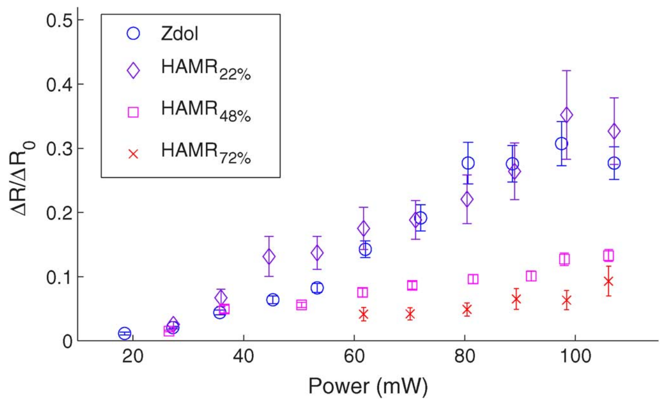

Fig. 6. Normalized reflectance change as a function of average laser power at constant exposure time ($t_{\mathrm{exp}} = 400$ s).

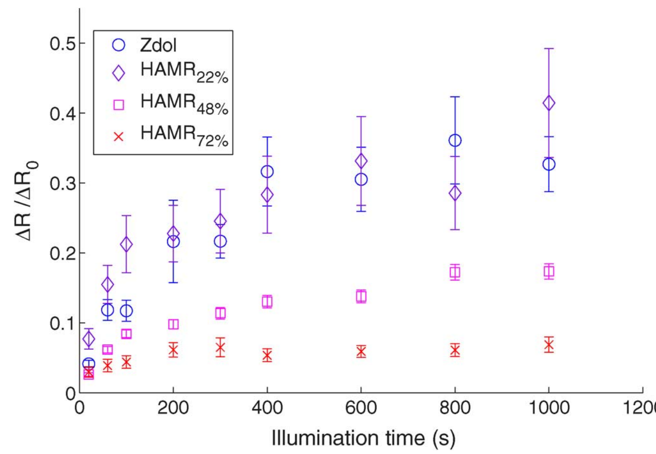

Fig. 7. Normalized reflectance change as a function of laser exposure time at constant laser power ($P = 107$ mW).

B. *Reflectance Change of Lubricant Thin Films Under Laser Beam Exposure*

Fig. 6 shows the normalized reflectance change $\Delta R/\Delta R_0$ of Zdol2000, $\mathrm{HAMR}_{22\%}$, $\mathrm{HAMR}_{48\%}$, and $\mathrm{HAMR}_{72\%}$ lubricant films as a function of the average laser beam output power, at constant laser beam exposure time of $t_{\mathrm{exp}} = 400$ s. We observe that the normalized reflectance change increases with an increase of the average laser power for all lubricants investigated, i.e., for Zdol2000, $\mathrm{HAMR}_{22\%}$, $\mathrm{HAMR}_{48\%}$, and $\mathrm{HAMR}_{72\%}$. The normalized reflectance change $\Delta R/\Delta R_0$ for Zdol2000 and $\mathrm{HAMR}_{22\%}$ is higher in comparison to $\mathrm{HAMR}_{48\%}$ and $\mathrm{HAMR}_{72\%}$. As the substitution ratio of modified Zdol lubricant increases, the rate of reflectance change decreases, under identical beam exposure conditions.

Fig. 7 shows the evolution of the normalized reflectance change $\Delta R/\Delta R_0$ of Zdol2000, $\mathrm{HAMR}_{22\%}$, $\mathrm{HAMR}_{48\%}$, and $\mathrm{HAMR}_{72\%}$ lubricant films as a function of laser beam exposure time, at constant average laser output power of $P = 107$ mW. We observe that the normalized reflectance change of the lubricant films increases with illumination time. In addition, $\mathrm{HAMR}_{48\%}$ and $\mathrm{HAMR}_{72\%}$ lubricant films undergo less change in reflectance under laser beam exposure compared to Zdol and $\mathrm{HAMR}_{22\%}$, i.e., the normalized reflectance change of modified Zdol decreases with an increase in the lubricant substitution ratio. The results of Figs. 6 and 7 show that the stability of modified Zdol lubricant films is improved compared to pure Zdol by substituting the OH end groups with a UV-stabilizer compound.

Using the model described in in Section II-B, we can relate the change of reflectance of a lubricant film to the variation of its optical properties or its thickness. Fig. 8(a) and (b) represent the theoretical normalized change of reflectance $\Delta R/\Delta R_0$ of a Zdol2000 lubricant film as a function of thickness (for a given index $n_0 = 1.31$) and refractive index (for a given thickness $d_0 = 1.8$ nm), respectively. We note that the lubricant refractive index and thickness correspond to the initial "as-coated" values for $\Delta R/\Delta R_0 = 0$.

We observe from Fig. 8 that a decrease in the lubricant thickness or refractive index causes an increase of the normalized reflectance change $\Delta R/\Delta R_0$. From Fig. 6, we note that the maximum experimentally measured value of $\Delta R/\Delta R_0$ for

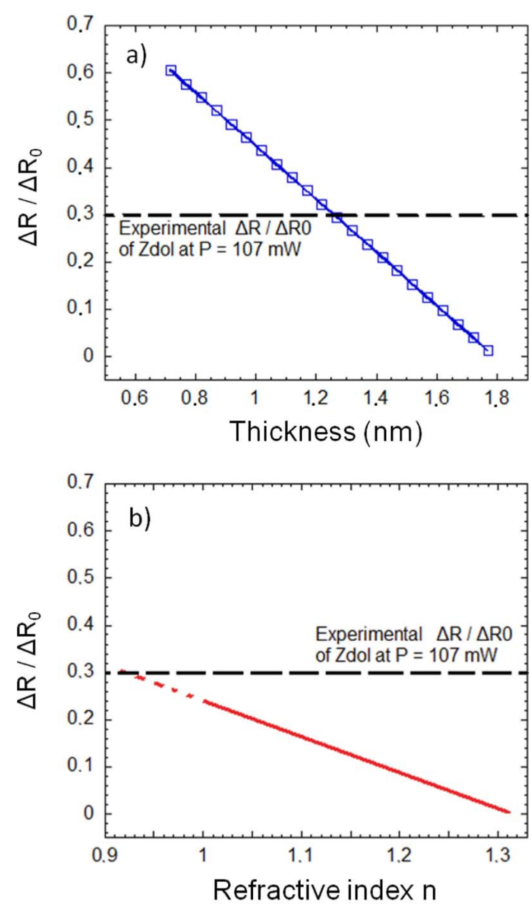

Fig. 8. Theoretical normalized reflectance change as a function of Zdol2000 lubricant thickness (a) and refractive index (b). The horizontal dashed line illustrates the experimental value of $\Delta R/\Delta R_0$ of Zdol2000 at maximum average power.

Zdol2000 is about 0.3 at an average power of 107 mW. Using this value of 0.3 in Fig. 8(a), we observe that a normalized reflectance change of 0.3 would correspond to a reduction of the lubricant thickness from 1.8 to 1.2 nm if lubricant depletion is assumed to be the only degradation mechanism. On the other hand, we observe from Fig. 8(b) that a value of $\Delta R/\Delta R_0 = 0.3$ would correspond to a reduction in the refractive index from 1.3 to about 0.9 if the refractive index change is assumed to be the only effect of laser beam exposure. However, this latter conclusion is unlikely since it would imply that the final refractive index is 0.9, a value that is smaller than that of air. A reduction in the lubricant thickness of 0.6 nm, as obtained if the reflectance change is only due to lubricant depletion, would be consistent with the removal of the lubricant mobile part under laser beam exposure. This observation is in agreement with Tagawa *et al.*'s work [8] who investigated the effect of lubricant depletion under laser exposure as a function of Zdol2000 film thickness and bonding ratio. Although it is unlikely that a modification of the lubricant refractive index n could account for a reflectance change $\Delta R/\Delta R_0 = 0.3$ since $n < 1$ would be required, it is possible that a combination of both lubricant depletion and modification of the lubricant optical properties under laser exposure is responsible for the reflectance change.

Tagawa *et al.* have studied the effect of laser beam exposure on lubricant films of different thickness [8]. They observed that depletion of the same lubricant under laser light exposure, for the same exposure duration, is a function of the initial thickness. These results have important consequences when dealing with lubricant films with different initial thickness or different optical properties and the effect of laser beam exposure on their reflectance properties. Lubricants such as modified Zdol with different substitution ratios are likely to have different optical properties and initial coating thickness compared to pure Zdol. While determination of a full set of optical and thermo-optical constants is beyond the scope of this work, our approach of using normalized reflectance data allows the evaluation of the photo-thermal stability of different lubricants under laser beam exposure independently of their initial thickness or optical properties.

The dependence between lubricant degradation due to laser beam exposure as a function of the substitution ratio is well correlated to the bulk lubricant thermal stability shown in Fig. 5, i.e., the bulk thermal stability increases as a function of the substitution ratio. Thus, it is justifiable to conclude that the photo-thermal stability of PFPE lubricant is enhanced by functionalizing the end groups using benzophenone.

C. Frictional Properties of Lubricant Thin Film Under Laser Beam Exposure

Fig. 9 shows the normalized friction force of Zdol2000, $\mathrm{HAMR}_{22\%}$, $\mathrm{HAMR}_{48\%}$, and $\mathrm{HAMR}_{72\%}$ lubricants measured prior to laser beam exposure (laser off) and after laser beam exposure (laser on), at constant disk velocity of 1 m/s. In the velocity range of 1 m/s, the asperities on the slider are in contact with the asperities on the disk, since at low speeds the air-bearing force separating the slider from the disk is negligible. Thus, the friction force at the slider/disk interface depends on interactions with the lubricant film on the disk. In Fig. 9 we compare the friction force at the slider/disk interface among different lubricants by normalizing the friction force to that of Zdol2000 prior to laser beam exposure. We observe that the normalized friction force of $\mathrm{HAMR}_{22\%}$ and $\mathrm{HAMR}_{48\%}$ prior to laser beam exposure is slightly higher than that of Zdol. In addition, we observe from Fig. 9 that the normalized friction

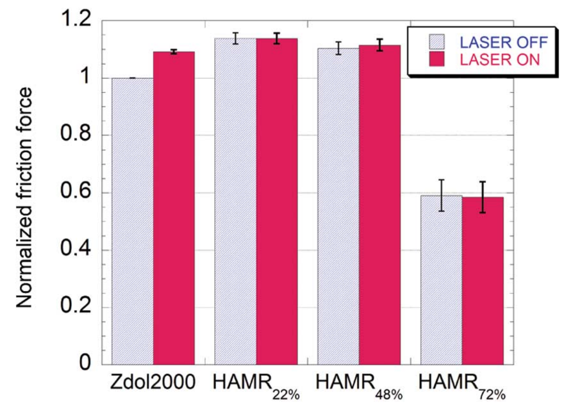

Fig. 9. Normalized friction force of Zdol2000, $\mathrm{HAMR}_{22\%}$, $\mathrm{HAMR}_{48\%}$, and $\mathrm{HAMR}_{72\%}$ at constant velocity of 1 m/s, before (laser off) and after (laser on) laser beam exposure of the wear track.

force of $\mathrm{HAMR}_{72\%}$ is the lowest among all lubricants evaluated. As the amount of benzophenone increases, the number of hydroxyl end groups responsible for bonding the lubricant to the disk surface is reduced. It is likely that this effect is responsible for the lower friction force of highly substituted PFPEs in comparison to Zdol2000.

In the case of Zdol, the normalized friction force (cf. Fig. 9) shows an increase of about 10% after laser beam exposure, compared to the normalized friction force prior to laser beam exposure. On the other hand, the normalized friction force of $\mathrm{HAMR}_{22\%}$, $\mathrm{HAMR}_{48\%}$ and $\mathrm{HAMR}_{72\%}$ remains unchanged after laser beam exposure.

IV. Discussion

In this work, the photo and thermal stability, as well as the frictional properties of modified Zdol2000 were investigated as a function of the substitution ratio under laser beam exposure. Our results indicate that the substitution of Zdol2000 OH end groups by benzophenone moieties improves the lubricant film photo-thermal and tribological properties under laser beam exposure. In our experiments, we have tested the tribological performance after long-time exposure of the lubricant film to laser radiation. In particular, we have studied the photo-thermal stability of modified Zdol lubricants using a 3 MHz pulsed, 660 nm wavelength laser beam applied for several minutes to a stationary disk. We estimate the average power density to be in the range from 10 to 100 $\mathrm{mW}/\mu\mathrm{m}^2$. HAMR systems operate with a laser beam applied to a rotating disk, with a pulse duration in the nanosecond range, at power densities that could reach several $\mathrm{W}/\mu\mathrm{m}^2$ [1], [2]. Thus the question arises as to whether the present long-time laser exposure experiment can predict the performance of a lubricant in a HAMR system where thermal stress is very different from our steady state experiments. Even though our experimental setup does not reproduce conditions of a HAMR system, we have developed an experimental method aiming at investigating photo-thermal and tribological properties of modified PFPE lubricants relative to pure PFPE lubricant, under laser irradiation. As a proof of principle, we have shown that the substitution of Zdol2000 OH end groups by benzophenone species leads to better photo-thermal stability and tribological performance under laser beam exposure than pure

Zdol2000. This trend was well correlated to the thermal stability of bulk modified Zdol2000 lubricants. It would be interesting to complete the thermal properties with absorption properties of modified Zdol2000 lubricants in the visible range.

Our work with functionalized Zdol suggests that the functionalization of OH end groups using benzophenone could be applied to other PFPE molecules used as disk lubricants, such as Ztetraol. The lubricant bonding between the modified PFPE lubricant film and the carbon overcoat should be studied since bonding takes place via the OH end groups that are being substituted by benzophenone.

Laser-induced temperature measurements are of importance to the understanding of lubricant degradation under laser beam exposure. In an attempt to evaluate laser-induced temperatures on a disk surface, a laser beam was directed at the surface of a disk and observed with a microscope sensitive to infra-red radiation. In this experiment, focusing of the laser beam was achieved to a spot size of only 100 μm in diameter under the microscope objectives. For this experimental setup, the measurements performed with a laser beam applied to a disk surface under an IR microscope indicate an average temperature rise of 35°C over a spot size of 100 μm in diameter. In this case, the setup configuration did not allow to focus the laser beam down to a micrometer size spot, thereby decreasing the power density by a factor of 10^4. This indicates that the optical power density is critical for achieving a temperature rise of several hundred degrees. Alternatively, laser-induced temperatures could be measured with a laser coupled to a spectrometer to obtain a micrometer sized laser spot on a disk surface and collect its Raman spectrum, at various incident laser powers. The Raman shift or the Stoke/anti-Stoke peak ratio of spectral features from a disk could be monitored as a temperature indicator at the laser spot with micrometer spatial resolution [17], [18]. For calibration purpose, the Raman spectrum of a disk homogeneously heated at a given temperature would be recorded and compared to the Raman spectrum obtained at various laser powers.

V. Conclusions

Modified Zdol lubricant films with different substitution ratios were investigated under laser beam exposure. The normalized reflectance change of modified Zdol films were found to be sensitive to laser beam exposure and was interpreted as a result of lubricant loss in the region exposed to the laser beam. Modified Zdol films show less reflectance change than Zdol, indicating higher stability under laser beam exposure. Photo-thermal stability of modified Zdol films under laser beam exposure increases with an increase of the substitution ratio. This result correlates well with the bulk thermal stability of modified Zdol lubricant versus their substitution ratio. A substantial increase of the normalized friction force of pure Zdol was observed after the wear track on the disk was exposed to the laser beam, while the friction force of modified Zdol lubricants was less sensitive under laser beam exposure and remained constant. Based on these results, we can conclude that PFPE molecules modified with benzophenone compounds are potential candidates applicable to HAMR systems. Future research should focus on temperature measurements using Raman spectroscopy as a temperature indicator.

Acknowledgment

The authors would like to thank QFI corporation for their help with temperature measurements performed with an infra-red microscope (Infrascope instrument). The disks substrates and the sliders were provided by Hitachi and Seagate corporations, respectively. This work was supported in part by a grant from the Information Storage Industry Consortium (INSIC).

References

[1] W. A. Challener, C. Peng, A. V. Itagi, D. Karns, W. Peng, Y. Peng, X. Yang, X. Zhu, N. J. Gokemeijer, Y. T. Hsia, G. Ju, R. E. Rottmayer, M. A. Seigler, and E. C. Gage, "Heat-assisted magnetic recording by a near-field transducer with efficient optical energy transfer," *Nature Photon.*, vol. 3, no. 5, pp. 220–224, 2009.

[2] B. C. Stipe, T. C. Strand, C. C. Poon, H. Balamane, T. D. Boone, J. A. Katine, J.-L. Li, V. Rawat, H. Nemoto, A. Hirotsune, O. Hellwig, R. Ruiz, E. Dobisz, D. S. Kercher, N. Robertson, T. R. Albrecht, and B. D. Terris, "Magnetic recording at 1.5 $\mathrm{pb\ m^{-2}}$ using an integrated plasmonic antenna," *Nature Photon.*, vol. 4, pp. 484–488, 2010.

[3] M. H. Kryder, E. C. Gage, T. W. McDaniel, W. A. Challener, R. E. Rottmayer, G. Ju, Y.-T. Hsia, and M. F. Erden, "Heat assisted magnetic recording," *Proc. IEEE*, vol. 96, no. 11, pp. 1810–1835, 2008.

[4] L. Li, P. Jones, and Y.-T. Hsia, "Effect of chemical structure and molecular weight on high-temperature stability of some Fomblin z-type lubricants," *Tribol. Lett.*, vol. 16, pp. 21–27, 2004.

[5] C. Mate, Q. Dai, R. Payne, B. Knigge, and P. Baumgart, "Will the numbers add up for sub-7-nm magnetic spacings? Future metrology issues for disk drive lubricants, overcoats, and topographies," *IEEE Trans. Magn.*, vol. 41, no. 2, pp. 626–631, 2005.

[6] L. Zhu and T. Liew, "Spectral characterization of perfluoropolyethers lubricant irradiated by laser light," *Appl. Surf. Sci.*, vol. 203–204, pp. 871–874, 2003.

[7] N. Tagawa, R. Kakitani, H. Tani, N. Iketani, and I. Nakano, "Study of lubricant depletion induced by laser heating in thermally assisted magnetic recording systems; effect of lubricant film materials," *IEEE Trans. Magn.*, vol. 45, no. 2, pp. 877–882, 2009.

[8] N. Tagawa, H. Andoh, and H. Tani, "Study on lubricant depletion induced by laser heating in thermally assisted magnetic recording systems: Effect of lubricant thickness and bonding ratio," *Tribol. Lett.*, vol. 37, no. 2, pp. 411–418, 2010.

[9] J. Lee, S.-W. Chun, H.-J. Kang, and F. Talke, "The effect of UV stabilizer on the photo degradation of perfluoropolyether lubricants used in hard disk," *Tribol. Lett.*, vol. 28, pp. 117–121, 2007.

[10] H. Liu and B. Bhushan, "Nanotribological characterization of molecularly thick lubricant films for applications to MEMS/NEMS by AFM," *Ultramicroscopy*, vol. 97, no. 1–4, pp. 321–340, 2003.

[11] D. L. Klein and G. H. Vurens, "Optical Measurement System Using Polarized Light," U.S. Patent, 6,134,011.

[12] G. H. Vurens and D. L. Klein, "Composition and thickness distribution of carbon overcoat films on thin film magnetic disks studied with surface reflectance analyzers," *Proc. SPIE*, vol. 3619, pp. 27–34, 1999.

[13] D. L. Klein and G. H. Vurens, "Measurements of thin film disks by surface reflectance analysis," *Proc. SPIE*, vol. 3619, pp. 18–26, 1999.

[14] R. M. A. Azzam and N. M. Bashara, *Ellipsometry and Polarized Light*. Amsterdam, The Netherlands: North-Holland, 1989.

[15] P. B. Johnson and R. W. Christy, "Optical constants of transition metals: Ti, V, Cr, Mn, Fe, Co, Ni, and Pd," *Phys. Rev. B*, vol. 9, no. 12, pp. 5056–5070, 1974.

[16] R. W.-J. Chia, E. Li, S. Sugi, G. G. Li, H. Zhu, A. R. Forouhi, and I. Bloomer, "Optical characterization of nitrogenated carbon overcoats," *Thin Solid Films*, vol. 308–309, pp. 284–288, 1997.

[17] H. W. Lo and A. Compaan, "Raman measurements of temperature during cw laser heating of silicon," *J. Appl. Phys.*, vol. 51, no. 3, pp. 1565–1569, 1980.

[18] M. Yamada, K. Nambu, Y. Itoh, and K. Yamamoto, "Raman microprobe study on temperature distribution during cw laser heating of silicon on sapphire," *J. Appl. Phys.*, vol. 59, no. 4, pp. 1350–1354, 1986.