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Lubricant reflow after laser heating in heat assisted magnetic recording

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In heat assisted magnetic recording (HAMR) technology for hard disk drives, the media will be heated to about 500 °C during the writing process in order to reduce its magnetic coercivity and thus allow data writing with the magnetic head transducers. The traditional lubricants such as Z-dol and Z-tetraol may not be able to perform in such harsh heating conditions due to evaporation, decomposition and thermal depletion. However, some of the lubricant depletion can be recovered due to reflow after a period of time, which can help to reduce the chance of head disk interface failure. In this study, experiments of lubricant thermal depletion and reflow were performed using a HAMR test stage for a Z-tetraol type lubricant. Various lubricant depletion profiles were generated using different laser heating conditions. The lubricant reflow process after thermal depletion was monitored by use of an optical surface analyzer. In addition, a continuum based lubrication model was developed to simulate the lubricant reflow process. Reasonably good agreement between simulations and experiments was achieved. © *2015 AIP Publishing LLC*.
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I. INTRODUCTION

In current hard disk drives (HDDs), nanometer-thick lubricant layers are applied on the surface of the media to provide protection for the heads and disks, by reducing the friction and wear during accidental slider disk contact.[1] The lubricant films are synthesized from Perfluoropolyether (PFPE) molecules, e.g., Z-tetraol, which are stable enough to protect the disk at and around room temperature for at least five years.

On the other hand, high magnetic anisotropy materials need to be used to break the limit of superparamagnetism in order to increase storage areal density beyond 1Tb/in.^{2}. The magnetic state of this kind of media is so stable at room temperature that current magnetic transducers may not be able to switch its orientation. Therefore, heat assisted magnetic recording (HAMR) technology[2,3] has been proposed to solve this problem. In HAMR, the magnetic layer is heated up to its Curie temperature with a laser such that the magnetic coercivity of the media is reduced and data writing with the magnetic transducers is possible.

Since the lubricant layer is on top of the magnetic layer, it will also be heated locally to a similar temperature. The harsh heating condition can damage traditional lubricants and reduce their lifetime due to evaporation, decomposition and thermal depletion.[4,5] However, some of the lubricant depletion can be recovered due to reflow after some period of time. The reflow behavior can help to cure the lubricant depletion and reduce the chance of hard head disk interface (HDI) failure. It is therefore important to understand the mechanisms and characteristics of the lubricant reflow behavior for HAMR systems.

In this paper, experimental studies of lubricant reflow were performed in a HAMR test stage for a Z-tetraol type lubricant. Section II describes the experimental setup. The observed reflow behavior of the lubricant is discussed in Sec. III. Section IV introduces a numerical model for lubricant reflow and compares the numerical simulation with our experimental results.

II. EXPERIMENTAL CONDITIONS AND PROCEDURE

A HAMR test stage was built to provide HAMR-like heating conditions on the disk and study the lubricant depletion and reflow behavior. The test stage contains the following three parts: an illumination module that can generate a laser beam at different power levels and focus the laser spot onto the disk with a size of a few microns, a spindle stage that can spin a disk at a controlled speed, and a servo motor that can control the radial movement of the laser spot such that different parts of a disk can be heated by the laser. A schematic drawing of the test system is shown in Fig. 1.

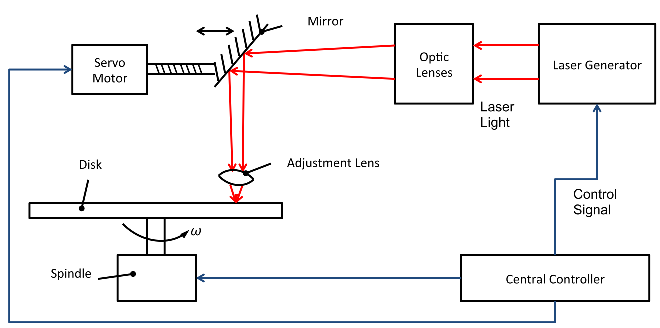

FIG. 1. Schematic drawing for the HAMR test stage. The Central Controller is for the spindle, the Laser Generator, and the Servo Motor. The Laser Generator illuminates the spinning disk with a laser light. The Servo Motor controls the objective lens such that different parts can be exposed to the laser.

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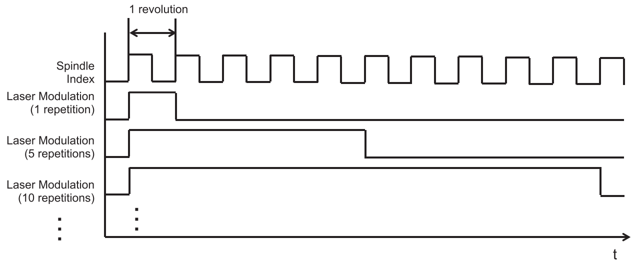

FIG. 2. Modulation of laser by spindle index.

Since HAMR disks were unavailable to us, commercial Perpendicular Magnetic Recording (PMR) disks were used instead in this investigation. The disks were 3.5 in. in diameter with aluminum substrates. The lubricant type was Z-tetraol with A20H additives, 60% bonding ratio and thickness of 9.5 Å.

As shown in Fig. 1, a laser spot generated from the illumination module was focused on the spinning disk. The laser spot heats up the disk and provides a HAMR-like condition. This illumination procedure contains three controllable parameters: laser power incident on the spinning disk (P_{inc}), disk's spinning speed (ω_{disk}) and number of disk revolutions (repetitions) during laser illumination (n_{illum}). P_{inc} was controlled by optical filters between the laser generator and disk; ω_{disk} and n_{illum} were controlled by an in-house designed electronic controller based on a field programmable gate array (FPGA) board. The optical encoder in the spindle was used to count the number of revolutions of the disk. The laser illumination repetitions (n_{illum}) can be precisely controlled. The relationship between repetitions and laser illumination time is shown in Fig. 2.

The disk was exposed to the laser at a constant P_{inc} while spinning at a constant ω_{disk}. However, we used different values of n_{illum} from 1000 to 1 on different tracks. Soon after the laser exposure, the disk was measured by a Candela optical surface analyzer (OSA). The Q-Phase channel was used to measure the lubricant thickness change.[6] Scans by the OSA were taken periodically at room temperature at intervals of about 95-s up to about 22 min in total such that the lubricant profile could be recorded at different times. A scan was also taken again after 24 h to see the final state of the lubricant.

III. LUBRICANT REFLOW PROCESS

Due to spindle run-out, the Q-phase image of the lubricant showed some curvature and background. A script was developed to post process the images and eliminate the run-out curvature and non-uniform background. Examples of the processed OSA images are shown in Fig. 3.

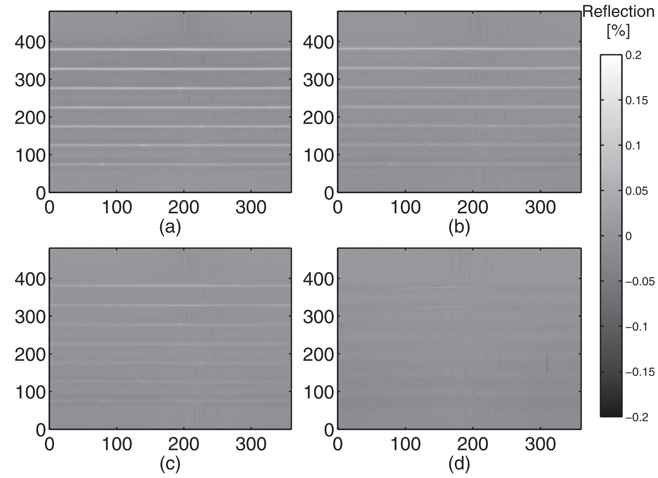

FIG. 3. OSA scanning images of relative reflectivity on a disk after certain repetitions of illumination by laser at: (a) 0 min, (b) 3 min, (c) 9 min, and (d) 24 h, respectively. The x-axis is the angular position in units of degrees and the y-axis is the relative radial position in units of μm. The relative reflectivity slowly fades as time elapses. The n_{illum} from top to bottom for the seven tracks are 1000, 500, 100, 50, 10, 5, 1, respectively.

As can be seen in Fig. 3(a), the parallel lines represent the exposed tracks to the laser for different n_{illum}. The increase of reflectivity in the Q-Phase indicates a lubricant thickness decrease. This is mainly due to lubricant depletion. Higher n_{illum} causes significantly more lubricant depletion as shown in Fig. 3 where the tracks on the top have a larger change of reflectivity. Figures 3(b) and 3(c) show the OSA Q-phase images after some time has elapsed. The reflectivity change of the tracks shown in Figs. 3(b) and 3(c) becomes smaller compared to Fig. 3(a), indicating that the lubricant flows back to the depleted region. Fig. 3(d) shows the reflection of the lubricant after 24 h. Fig. 3(d) shows no apparent reflection when $n_{illum} \leq 100$, which means that the lubricant has recovered back to its initial state. However, when $n_{illum} > 100$, there still remain some changes of reflectivity which were not recovered in 24 h of lubricant reflow. This final state condition may be due to degradation of the carbon overcoat (COC) or magnetic layers.[4] To eliminate possible non-lubricant effects, only the $n_{illum} \leq 100$ conditions are discussed below.

Figure 4 shows the maximum lubricant depletion depth as a function of time for one set of experiments. The

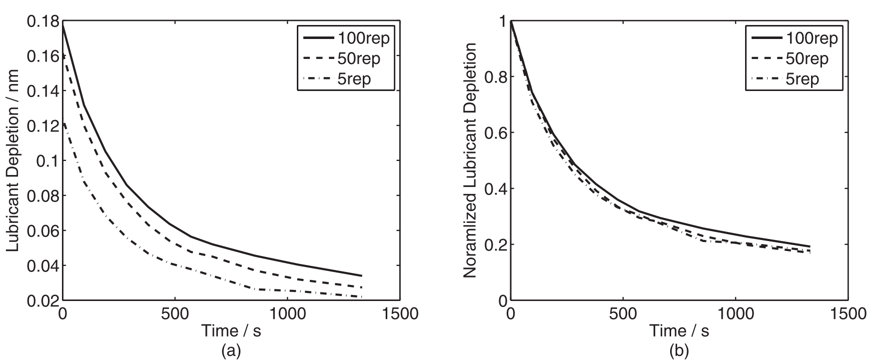

FIG. 4. Lubricant relaxation after laser depletion. (a) The three different lines show different laser illumination repetitions. Less repetitions result in shallower initial lubricant depletion. The reflow trends are similar for the three different conditions. (b) Lubricant depletion normalized with respect to initial value. The depletion is set to 1 at t = 0. Similar trends are shown.

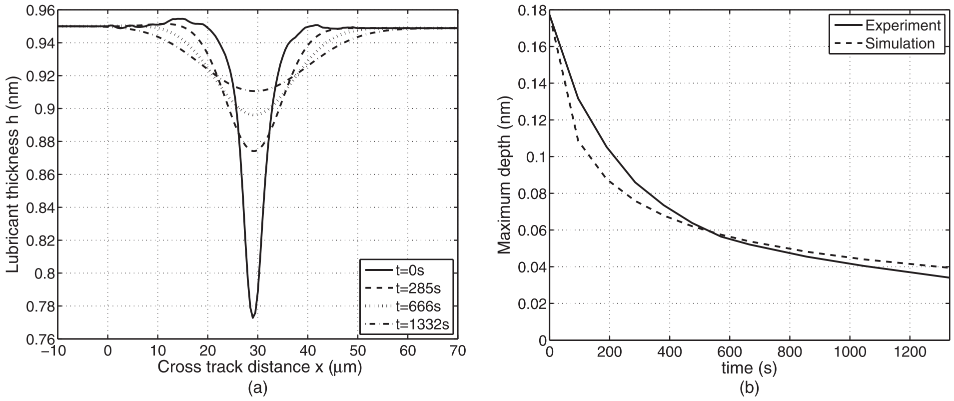

FIG. 5. (a) Film thickness profile at selected times obtained from simulations. (b) Depth of the maximum depletion point in the film as obtained from experiments and results. The experiment parameters are $\omega_{disk} = 600$ RPM, $P_{inc} = 165$ mW and $n_{illum} = 100$. The simulation parameters are $\mu = 1.5\,\mathrm{Pa}\cdot\mathrm{s}$ and $A = 1 \times 10^{-21}$J.

lubricant depletion and reflow profiles were obtained from the OSA Q-phase images, some of which were shown in Fig. 3. The experimental parameters used in Fig. 4 are ω_{disk}=600 RPM and P_{inc}=165 mW. The illumination repetitions were 100, 50, and 5, respectively. The depletion curve with $n_{illum} = 1$ was too small for a reliable analysis, therefore these result is not presented.

As shown in Fig. 4, the lubricant depletion is more severe when the disk is illuminated for more repetitions. To exclude the effect of different initial lubricant depletion on the reflow, we normalized the lubricant depletion curves by its initial value as shown in Fig. 4(b). It is observed that the lubricant depletion decreases as time elapses, which indicates that the lubricant flows back into the depleted area. The reflow rate is initially fast and decreases with time. Almost 80% of the lubricant recovers within 20-min of relaxation at room temperature.[7]

IV. COMPARISON BETWEEN SIMULATION AND EXPERIMENTS

Simulations of lubricant reflow were carried out to compare them with the experimental results. The lubricant reflow was described using continuum theory with a modified (effective) viscosity.[8] Within the continuum approach, the dimensions of the thin film on the disk surface make it possible to use lubrication theory and thus we obtain the governing equations described below

$$\frac{\partial h}{\partial t} + \frac{1}{3\mu}\frac{\partial}{\partial x}\left[h^3 \frac{d\Pi(h)}{dh}\frac{\partial h}{\partial x}\right] = 0\,, \qquad (1)$$

where $h = h(x,t)$ is the film thickness, μ is the effective lubricant viscosity, $\Pi(h)$ is the disjoining pressure arising from van der Waals interactions between the lubricant and the solid substrate.[9] This disjoining pressure is of the form $\Pi(h) = Ah^{-3}$, where A is the Hamaker constant. The initial condition, as seen in Fig. 5(a), was given by the lubricant depletion profile obtained in the experiments at time $t = 0s$. As boundary conditions, we considered zero volume flow at the right and left boundaries. This condition is equivalent to setting $dh/dx = 0$ at the boundaries. It can be observed that Eq. (1) depends only on the ratio of the Hamaker constant to lubricant viscosity. This ratio was adjusted to give the best match to the experimental results. The simulation results of lubricant reflow are shown in Fig. 5.

It can be seen from Fig. 5(b) that the simulation results fit adequately the experimental data. However, there exist regions of some discrepancy. In the first 400 s of reflow, the simulation results show a faster recovery rate than the experiments. After this time, the reflow in the simulation slows down relative to the experiments. This discrepancy may be explained by noting that the lubricant viscosity of thin films can be thickness dependent as discussed in Ref. 10. This phenomenon was not included in the present simulation model.

V. CONCLUSION

In this paper, the thermal depletion behavior of Z-tetraol due to a free laser beam heating condition as well as the recovery behavior after heating was studied. The initial lubricant depletion was different for different laser heating conditions, i.e., a longer heating duration causes more lubricant depletion. However, a similar trend was found regardless of initial lubricant depletion. Almost 80% of lubricant reflows back within 20 min at room temperature. Simulation results show a reasonably good agreement with experiments.

Real HAMR laser conditions use a near field transducer (NFT) as a heating method to achieve heated spots of tens of nanometers rather than a few microns. So the NFT heating has a spot size a few orders of magnitude smaller and its duration is a few orders of magnitude shorter than our free laser beam heating. Further study will be made with the NFT heating and HAMR disks as soon as the needed components become available.

ACKNOWLEDGMENTS

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