Slider-Lubricant Interactions and Lubricant Distribution for Contact and Near Contact Recording Conditions

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Abstract

Lubricant distribution and recovery for near contact and contact recording conditions are experimentally investigated using Thermal Fly-height Control (TFC) sliders. Contact between the protruded center pad and the disk lubricant causes a thickness modulation (rippling) together with lubricant depletion that grows with contact duration. Slider dynamics and lubricant rippling evolve quickly in the first few revolutions of contact and rippling frequencies are strongly correlated with the slider air bearing frequencies. Peculiar cases where suppressed 'stable' slider dynamics occur for TFC heater power beyond the touchdown power correspond to negligible lubricant rippling and this condition may be sustained for fairly long durations in some tests. Experiments with different lubricant types (ZTMD, Z-tetraol+A20H, Z-dol+A20H) and different lubricant thicknesses show that a larger depletion is observed for the thicker lubricant of each type at a given TFC heater power. Lubricants with lower bonded fraction show shorter recovery time after the slider is unloaded. From the current experiments it is extrapolated that Z-dol+A20H (30% bonded) lubricant recovers in a time scale of a few hours, while Z-tetraol+A20H (60% bonded) lubricant of comparable thickness takes a few days, and ZTMD (75% bonded) takes weeks to fully recover.

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I. INTRODUCTION

Interactions between the slider and the disk lubricant have become increasingly important as the head-disk clearance shrinks to the subnanometer regimes. Abundant literature exists documenting the detrimental effects of slider-lubricant interactions on slider dynamics and on head-disk interface (HDI) performance. The coupled effect of slider dynamics and lubricant modulation on each other (washboarding effect) is a serious concern for HDI reliability [1]. Even for a noncontacting interface, lubricant transfer from disk to slider occurs by evaporation/condensation mechanisms and is enhanced by flow and accumulation of the lubricant on the slider's trailing end [2]. Lubricant drop-off from the slider's trailing end to the disk has been experimentally observed and is known to cause magnetic spacing changes that are detrimental to read-write performance [3, 4]. Apparent spacing increases due to lubricant accumulation on the slider's trailing end and the associated 'waterfall effect' pose a challenge to the reliable measurement and calibration of the read-write head clearance in a working drive [5, 6].

Future magnetic storage density targets necessitate clearances of $0.25nm$ which essentially falls in the realm of recording with intermittent and possibly continuous contact with the lubricant and disk media. Slider-lubricant contact is expected to significantly alter and enhance the slider-lubricant interactions, and therefore it requires investigation. Recently, the feasibility of recording in a lubricant-surfing regime has been explored [7]. Interesting experimental observations have been reported for slider dynamics in the lubricant-contact regime [8] and have been partially explained using nonlinear systems theory [9]. However, the challenge of fully understanding slider-lubricant interactions in the presence of contact still remains and forms an important basis for developing proper design strategies to ensure the long term reliability of a contacting HDI.

Considering the above motivation, this work focuses on experiments to study lubricant distribution and slider-lubricant interactions using Thermal Fly-height Control (TFC) actuation to bring the slider's read-write head region into proximity and contact with the disk lubricant. The experiments are designed to understand lubricant distribution under the thermal protrusion as well as subsequent recovery of the distributed lubricant after contact/near contact tests. The correlations between slider dynamics and contact conditions with lubricant distribution are highlighted. Finally, the net lubricant depletion under the thermal protrusion and the recovery times for the distributed lubricant are reported for the different lubricant types and thicknesses used in this study.

II. EXPERIMENTS

The experiments are conducted on a spinstand equipped with an optical surface analyzer (OSA) for *in-situ* monitoring of the lubricant surface. This set-up allows the observation of the change to the lubricant surface as the slider continues to fly over the test track, and permits the understanding of how the lubricant recovers/reflows after the slider is unloaded from the test track. The slider's vertical motion is simultaneously monitored using a laser doppler vibrometer (LDV), which is used for correlation with lubricant distribution results.

Previous investigations have shown peculiar slider dynamics when the heater power is increased beyond the touchdown power (TDP). Specifically, the suppression of the intensity of acoustic emission (AE) detected contact and the magnitude of slider motions in all directions (vertical, down-track and off-track) has been reported [8] and shown to be attributable to nonlinearities at the HDI [9]. The correlation of lubricant distribution with the slider dynamics in this regime is important and is reported in this work. The results for cases when the heater power is reduced below the TDP (backoff), is at the TDP and is above the TDP (overpush) are compared to understand the interplay between slider dynamics and lubricant distribution.

The research disks used in this work are coated with different lubricants: Z-dol+A20H (30% bonded) with thickness 9.5Å and 13.7Å, Z-tetraol+A20H (60% bonded) with thickness 9.5Å and 14.5Å, and ZTMD ($>75\%$ bonded) with thickness 10.5Å, 12Å and 14Å. The test procedure is as follows: after calibrating the TDP on the test track, the slider is flown with the TFC heater turned 'on' over only one half of the track every disk revolution by synchronizing the heater power input program to the spindle index. By controlling the heater power to be below the TDP (for backoff), at TDP or above the TDP (for overpush), this testing protocol gives good control to observe and compare changes to the lubricant without any thermal protrusion (part of the track with heater turned 'off') and with specified thermal protrusion (part of the track with heater turned 'on'). Additional information on the lubricant behavior in the region where the thermal protrusion comes into contact and leaves contact with the disk lubricant may also be obtained using this method. Fig 1 shows a representative OSA scan of the disk lubricant before and after a test with many cycles of overpush power on one half of the test track. While there is negligible change in the lubricant surface with no thermal protrusion (zero heater power), significant change in the lubricant is observed where the thermal protrusion causes lubricant/disk contact. In the OSA scans that follow, the light and dark regions represent lubricant depletion and accumulation, respectively.

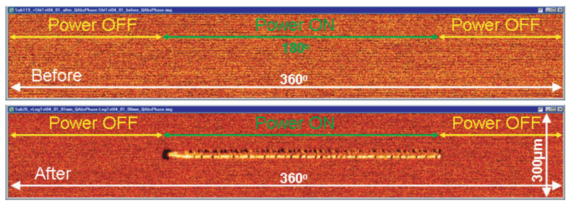

FIG. 1. Representative OSA scan before and after a test with the heater turned 'on' over one half of the test track

III. RESULTS AND DISCUSSION

A. Correlating lubricant and slider dynamics

In order to correlate the lubricant and slider dynamics a test is performed to monitor the change to the lubricant surface after 50 synchronized pulses to the TFC heater (i.e. contacting one half of the disk track 50 times). The OSA scans before and after this test give the cumulative change to the lubricant and the LDV data is used to obtain information on how the slider dynamics changes with contact from the first to the 50^{th} pulse.

Fig 2a shows the lubricant profile for tests on a disk with ZTMD lubricant of 14Å thickness with TFC heater power of TDP$-5mW$ (i.e. $5mW$ backoff), TDP, TDP$+10mW$ (i.e. $10mW$ overpush) and TDP$+20mW$ (i.e. $20mW$ overpush). Significant lubricant rippling occurs in this case at TDP and in overpush conditions. Fig 2b shows the frequency content of the lubricant rippling appearing in Fig 2a together with the slider's vertical velocity spectrum for the first and 50^{th} contact pulse at each power level. Frequencies above $50kHz$ (corresponding to the ABS frequencies) are of primary importance in this work.

From Fig 2b, a few important observations can be made. First, slider dynamics evolves quickly and is different in the 50^{th} pulse compared to the first pulse. This observation is very

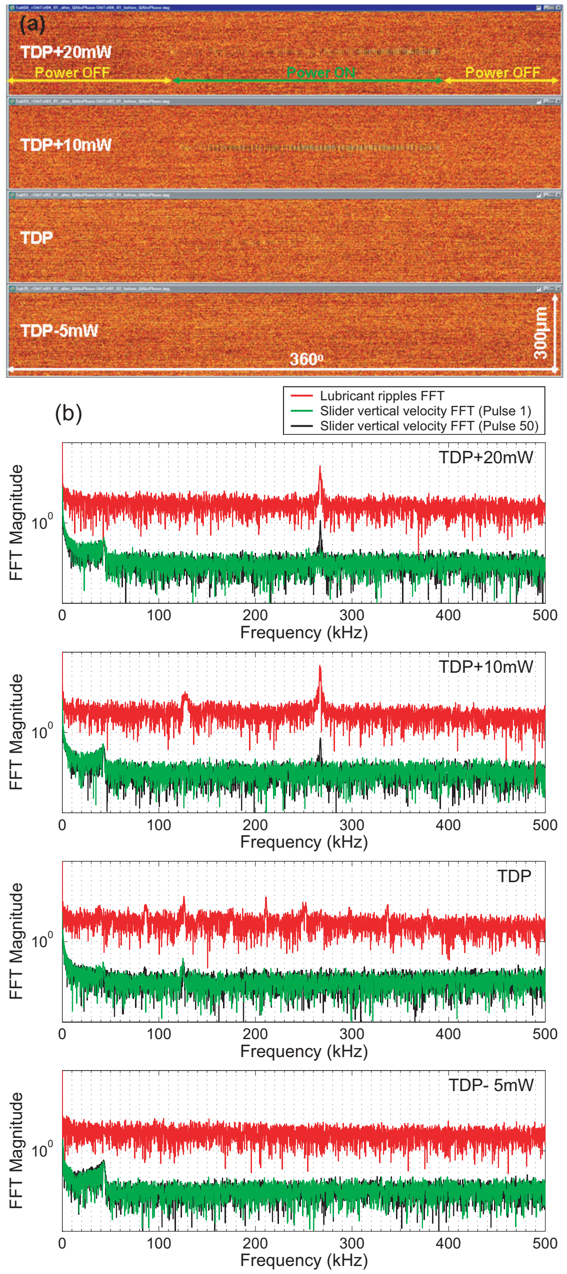

FIG. 2. Case with strong lubricant rippling and slider dynamics at TDP and in overpush (a) OSA scans showing lubricant surface change after tests with different heater powers (b) Spectrum of the lubricant profile under the thermal protrusion and spectrum of the slider's vertical velocity for the first and 50^{th} contact pulse

evident for the overpush cases in this figure and is marked by the appearance of a strong peak at $265kHz$ in the 50^{th} pulse. Second, the slider dynamics at TDP is different from slider dynamics in overpush as marked by the location of the frequency peak at $125kHz$

and $265kHz$, respectively, consistent with previously published literature showing the slider dynamics to be strongly dependent on the degree of contact [8, 10]. Third, the lubricant spectrum shows no specific peaks at backoff, but significant peaks occur at TDP and in overpush. Lubricant spectrum peaks, when they appear, correspond well with the frequency peaks in the slider's vertical velocity spectrum (of the 50^{th} pulse) verifying good correlation between the two. Slider dynamics and lubricant rippling are therefore well correlated with the dominant lubricant rippling frequencies matching the slider's vertical bouncing frequencies. It is concluded that lubricant and slider interactions evolve very quickly in the first few revolutions of contact through an interplay similar to the washboarding effect reported in literature [1].

The more interesting and peculiar case occurs when the slider dynamics and AE detected contact are suppressed in the overpush condition. The lubricant surface changes for such a case are shown in Fig 3a from experimental results using a disk with ZTMD lubricant of 12Å thickness. While there is stronger lubricant rippling at TDP, the lubricant rippling in overpush is negligible in comparison. The spectrum of lubricant profile shown in Fig 3b reveals the same information: no peaks are present for the TDP+10mW and TDP+20mW cases compared to peaks at $125kHz$ and $270kHz$ for TDP case. It is noted that slider's vertical velocity spectrum also shows the same trend, with no frequency peaks evident in overpush compared to the strong peak at $125kHz$ at TDP. These results once again show that slider dynamics and lubricant rippling are well correlated. Specifically, the absence of slider dynamics ('stable' condition) in overpush corresponds with the absence of lubricant rippling.

For this 'stable' case where the slider dynamics and lubricant rippling are both absent in overpush, the test is extended to understand the effect of continuing the contact pulses for a longer duration. Fig 4a shows the lubricant scans after applying TFC pulses on one half of the track for 1 minute ($\approx$ 3600 pulses) and Fig 4b shows the associated spectrum of slider dynamics and lubricant rippling. It is seen from Fig 4a that at TDP, the change to the lubricant is higher (with stronger evidence of lubricant rippling). The cases with overpush show lesser lubricant change except at the angular locations marking the onset and the end of contact. A zoomed image of these contact onset and contact end angular locations is shown in Fig 5a and Fig 5b, respectively. From Fig 5a, a region of lubricant accumulation at the onset of contact is observed suggesting the transfer of lubricant from the trailing end of

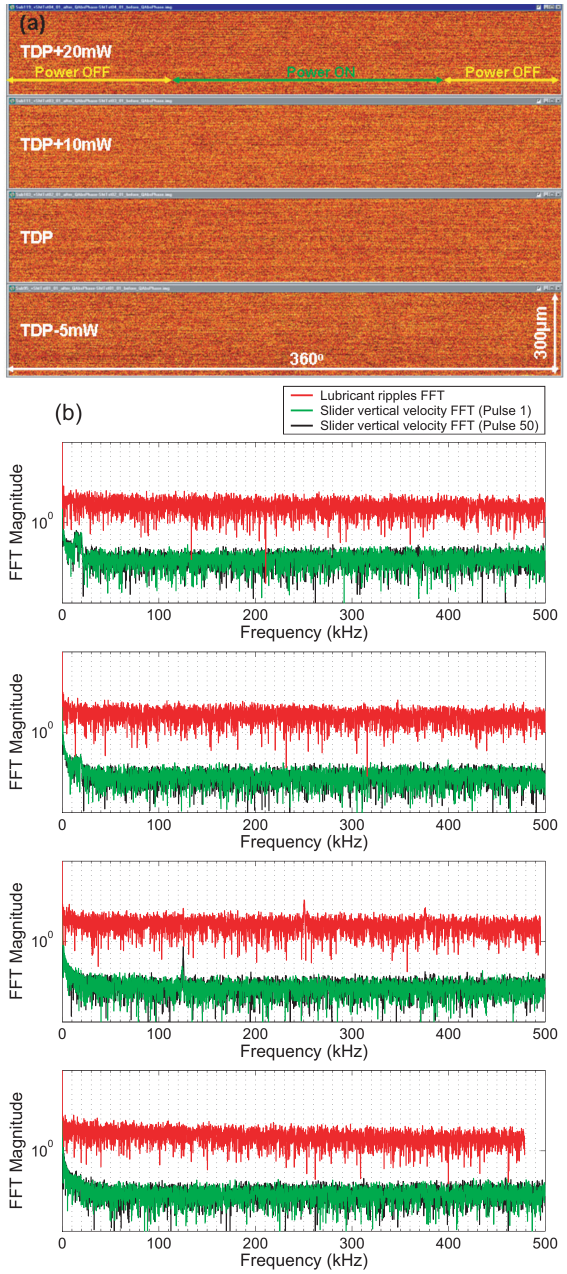

FIG. 3. Case with negligible lubricant rippling and slider dynamics in overpush (a) OSA scans showing lubricant surface change after 50 contact pulses for tests with different heater powers (b) Spectrum of the lubricant profile under the thermal protrusion and spectrum of the slider's vertical velocity for the first and 50^{th} contact pulse

the slider to the disk, which can be explained as follows: the increasing thermal protrusion causes a decreasing slider-disk clearance allowing the bridging of lubricant accumulated on the slider's trailing end with the disk thus facilitating lubricant transfer/drop-off onto the disk. Immediately following this lubricant accumulation region is a strong depletion zone with superposed lubricant rippling. For tests with heater power at TDP, this rippling signature continues for as long as the heater is turned 'on', but for the overpush conditions of TDP+10mW and TDP+20mW, the lubricant rippling ceases, leading to a region of negligible lubricant depletion or rippling. Although not shown here, it was possible to sustain such a condition of suppressed AE signal, suppressed slider dynamics and negligible lubricant change for as long as 20 minutes in some tests.

While it may be speculated that this zone with negligible lubricant change and 'stable' slider dynamics corresponds to that of smooth sliding over the lubricant surface (lubricant surfing regime), conclusive evidence and understanding of the slider-lubricant interactions in this interesting zone requires further research. Other possibilities include contact loss for short durations because the slider bounces off and attains a stable flying state without any lubricant contact. The durability of the interface while operating in this interesting zone also remains an open topic for investigation.

Another peculiar observation in these overpush tests is the presence of a strong depletion zone at the end of contact (Fig 5b) suggesting lubricant pick-up onto the slider as the TFC protrusion retracts when the heater is turned 'off'.

This study to understand lubricant and slider dynamics in contact reveals that lubricant rippling and slider dynamics frequencies are very well correlated. In particular the peculiar 'stable' condition with negligible slider dynamics in overpush corresponds with negligible lubricant ripping or negligible change to the lubricant surface. This 'stable' condition may be sustained for long durations in some tests, and is presumed to be depended in lubricant as well as slider design. The typical lubricant signature for overpush tests shows lubricant accumulation at the onset of contact, followed by a region of either a strong rippling with associated slider dynamics or a negligible lubricant change with 'stable' slider dynamics, followed by a strong depletion signature at the end of contact.

B. Lubricant evolution under the TFC protrusion

Lubricant evolution under the thermal protrusion as well as the subsequent relaxation/recovery of the displaced lubricant is performed using the following post processing steps on the OSA images. The averaged lubricant profile under the thermal protrusion

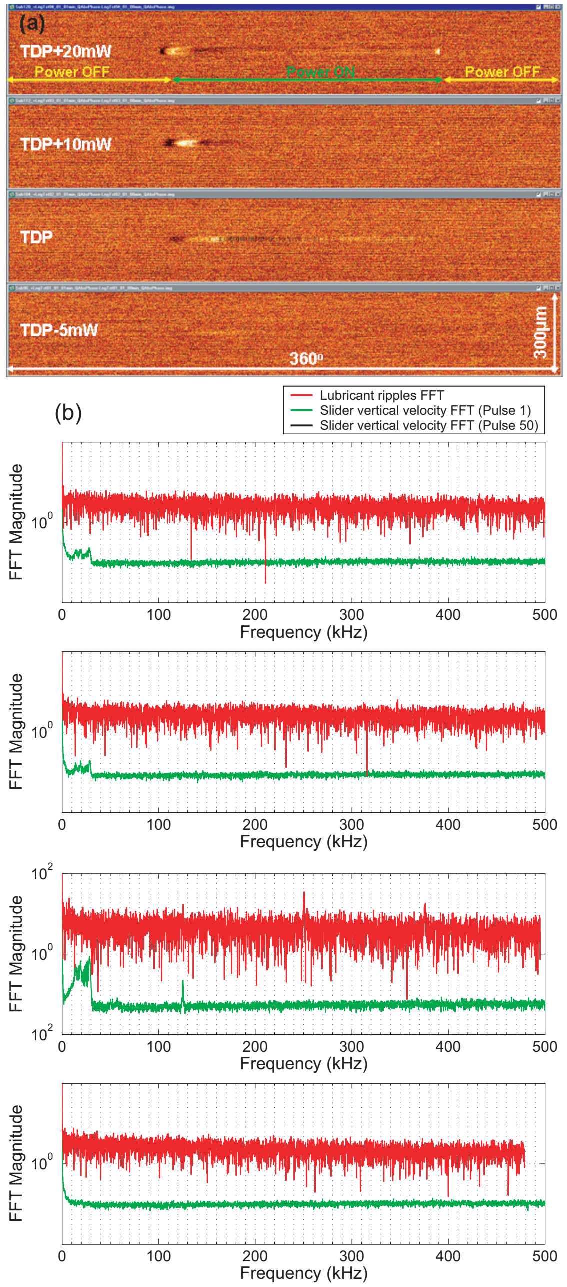

FIG. 4. Case with negligible lubricant rippling and slider dynamics in overpush (a) OSA scans showing lubricant surface change after 1 minute for tests with different heater powers (b) Spectrum of the lubricant profile under the thermal protrusion and spectrum of the slider's vertical velocity

is obtained over the track cross-section (Fig 6) and it typically shows a region of lubricant depletion (groove) under the TFC protrusion and occasionally a region of lubricant accumulation (ridge) on the side(s) of the TFC protrusion.

The net-depletion (defined as the volume of the groove less the volume of the ridge)

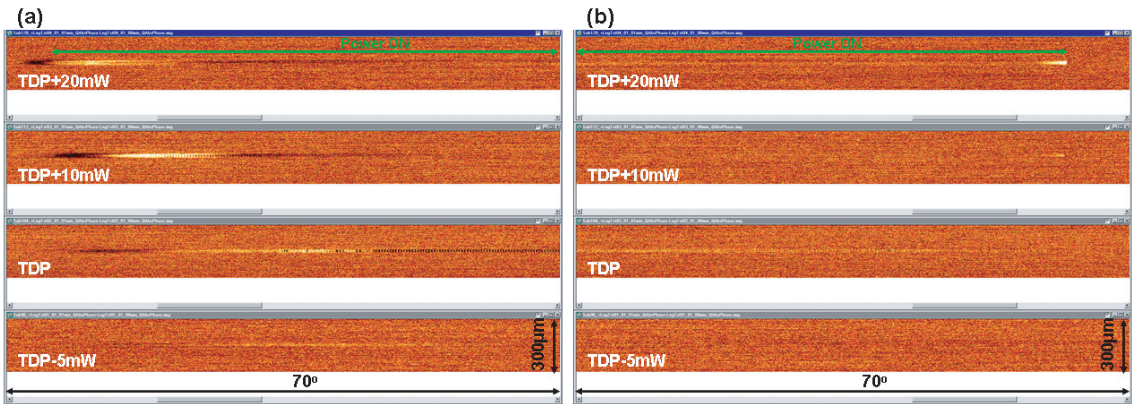

FIG. 5. Zoom image of OSA scans shown in Fig 4. (a) Contact onset region (b) Contact end region

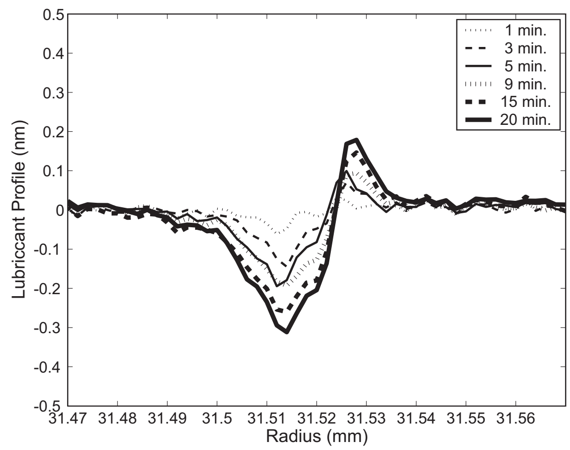

FIG. 6. Representative lubricant profile cross-section of the test track during a contact test

generally increases with duration of contact. Least depletion occurs at back-off powers and depletion is enhanced in overpush because slider-lubricant contact plays a more significant role in lubricant distribution compared to high pressure and shear induced lubricant redistribution at back-off powers.

Comparing Fig 7a and Fig 7b for ZTMD lubricant with thickness of 10.5Å and 14Å respectively, it is observed that at a given TFC (overpush) power, the thicker lubricant case has a greater depletion tendency. A similar result was obtained for Z-tetraol+A20H (Fig 8) and Z-dol+A20H (Fig 9) lubricant as well. It is expected that depletion increases with increasing heater power (i.e for decreasing clearance or increasing interference), but the trend may not always be obvious because slider-lubricant interaction causes complex phenomena such as occasional lubricant drop-off from the slider to the disk and lubricant changes due to occasional slider instability/bouncing periods, and they potentially introduce substantial test-to-test variations in the results.

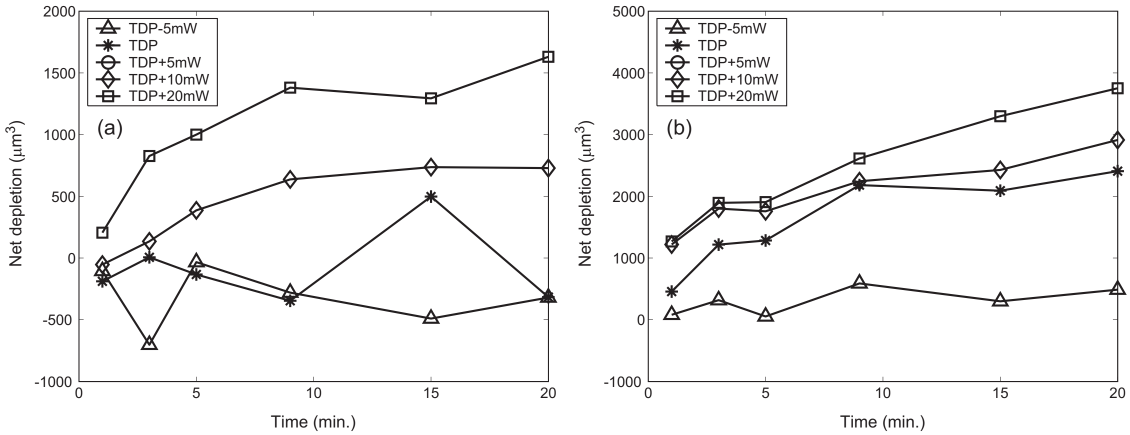

FIG. 7. Net-depletion with time (a) ZTMD 10.5Å (b) ZTMD 14Å

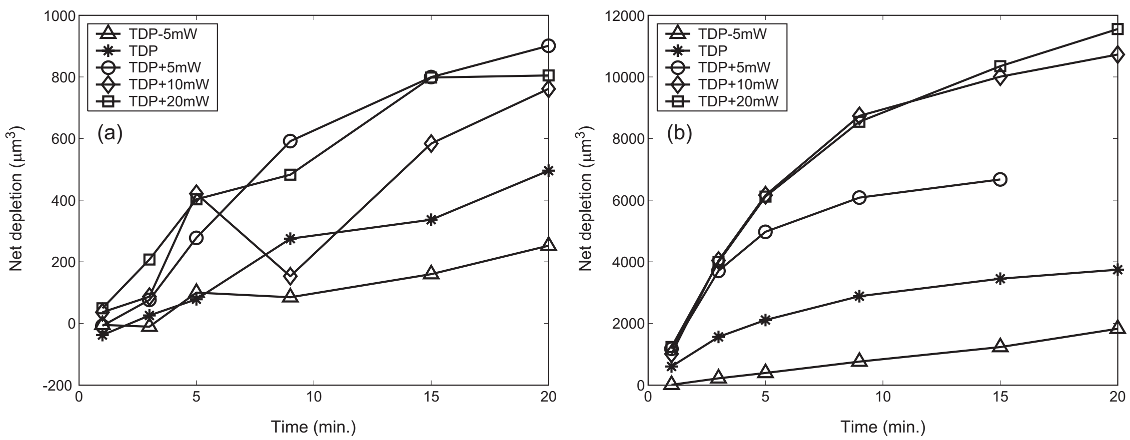

FIG. 8. Net-depletion with time (a) Z-tetraol+A20H 9.5Å (b) Z-tetraol+A20H 14.5Å

An important observation is that the net-depletion in overpush appears to be the least for the 'stable' case when slider dynamics or lubricant rippling is absent. As seen in Fig 10, the net-depletion for the 'stable' overpush case is significantly lower than the other two cases with 'unstable' behavior at overpush power, and it in fact compares closely to the case with $5mW$ back-off.

Lubricant recovery refers to the ability of the lubricant to recover back to a 'flat' profile (from those shown in Fig 6) after the slider is unloaded. This important metric is a measure of how quickly any contact related damage is 'healed' to ensure prolonged HDI reliability. In this work, the standard deviation (σ) of the profile shown in Fig 6 is used as a measure of

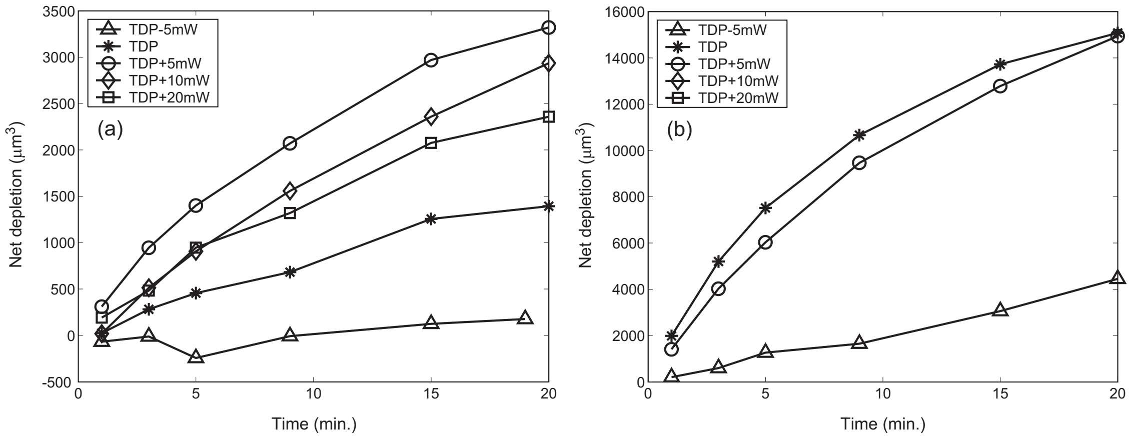

FIG. 9. Net-depletion with time (a) Z-dol+A20H 9.6Å (b) Z-dol+A20H 13.7Å

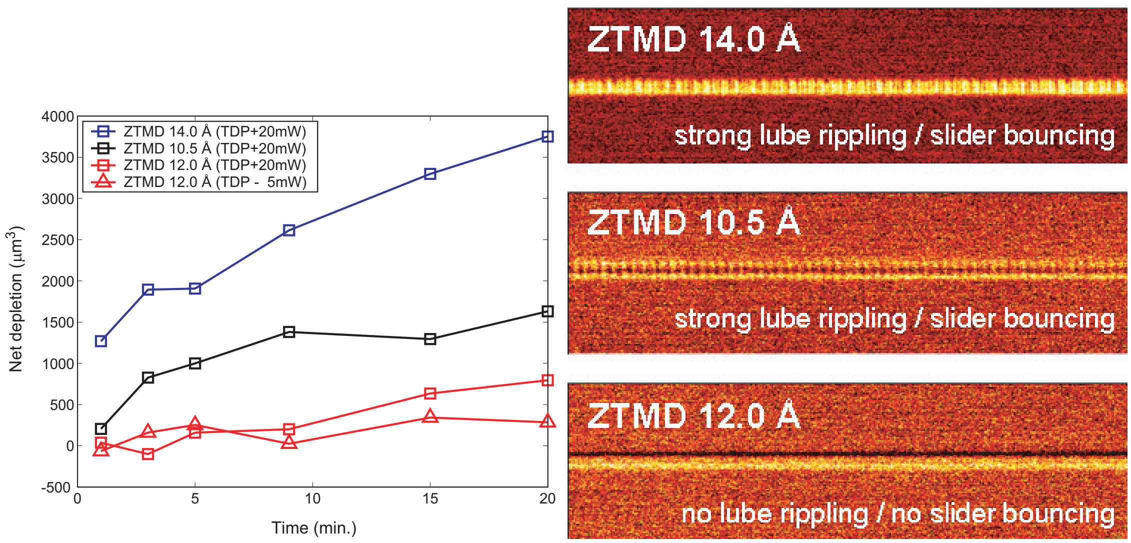

FIG. 10. Net-depletion vs. slider dynamics and lubricant rippling signature

lubricant surface 'nonflatness' ($\sigma = 0$ corresponds to a perfectly flat lubricant surface). After normalizing with the value of σ at one minute after slider unloading, the plots for lubricant recovery to flatness are shown for Z-dol+A20H lubricant and Z-tetraol+A20H lubricant in Fig 11. It is seen that after normalization, the dependence of the lubricant recovery curves on the actual heater power is minimal. So the lubricant recovery time obtained with $20mW$ overpush is similar to that with any other overpush power value. Good repeatability is observed between tests conducted on different days giving confidence in this method.

Using this method, the recovery times for the different lubricants used in this work are plotted in Fig 12. Lubricant recovery time is strongly influenced by the mobility of the

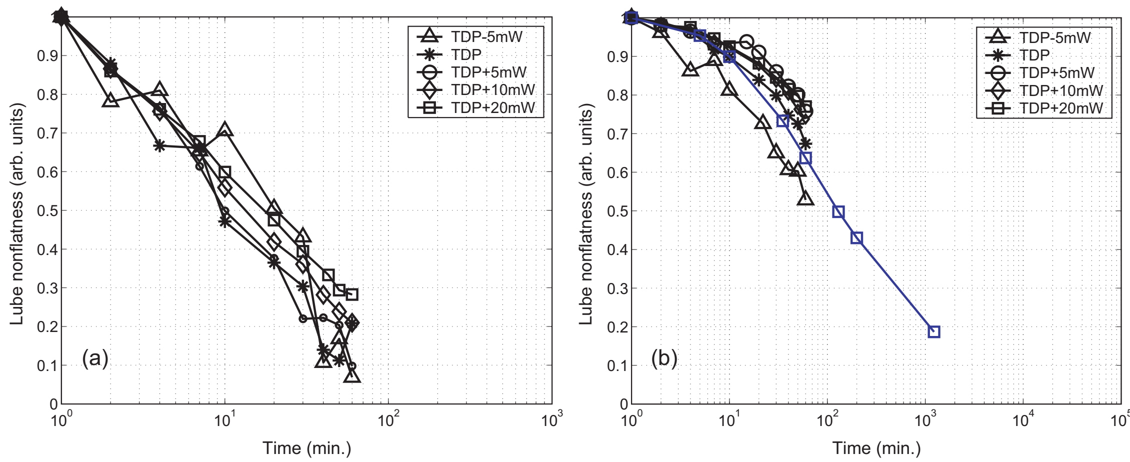

FIG. 11. Lubricant recovery to flatness with time (a) Z-dol+A20H 9.6Å (b) Z-tetraol+A20H 14.5Å, blue curve represents test conducted on different day

lubricant molecules. In the current experiments, Z-dol+A20H with higher mobile fraction (30% bonded fraction) recovered much quicker than Z-tetraol+A20H with lower mobile fraction (60% bonded), which in turn recovers quicker than ZTMD (> 75% bonded fraction). Based on the extrapolated data trends shown in Fig 12 it is concluded that the recovery time for Z-dol based lubricant is on the order of a few hours, that for Z-tetraol is a few days, and that for ZTMD is in weeks.

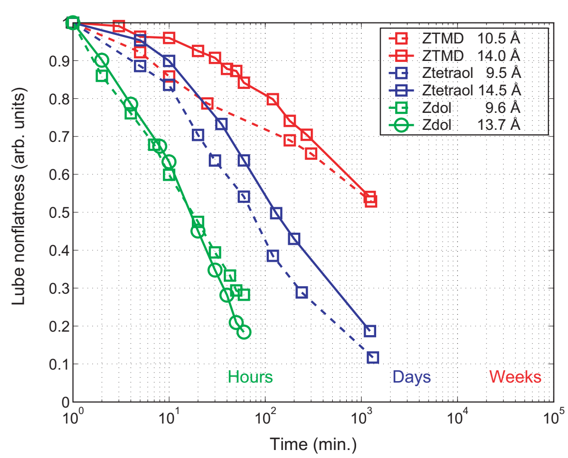

FIG. 12. Lubricant recovery plots for different lubricants

IV. CONCLUSION

Investigations to fully understand the effect of low clearances and contact on slider dynamics, lubricant distribution and slider-lubricant interactions are important in order to develop design strategies to meet overall HDI reliability goals in future hard-disk drives. The experimental results in this work reveal that under contact and overpush conditions slider dynamics and lubricant surface rippling are strongly correlated. In particular, the favorable condition with 'stable' slider dynamics in overpush is also associated with negligible change in the lubricant surface. The mechanism of lubricant transfer from the slider to the disk at the onset of contact as well as strong depletion at the end of contact is demonstrated. Results for lubricant distribution with different lubricant types and thicknesses reveal that the net-depletion is higher for thicker lubricant for all lubricant types. Extrapolated lubricant recovery times for the Z-dol based lubricant is shorter (hours) compared to the Z-tetraol based lubricant (days) and the ZTMD lubricant (weeks). Research to empirically relate lubricant evolution (net-depletion) and recovery times with lubricant properties is proposed as future work on this topic.

ACKNOWLEDGMENTS

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