Slider-Lubricant Interactions: Effect of Media-type, Lubricant Molecular Weight and Additives

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Abstract

As the head-disk spacing reduces in order to achieve the areal density goal of $1Tb/in.^2$, dynamic stability of the slider is compromised due to a variety of proximity interactions. Lubricant pickup by the slider from the disk is one of the major reasons for decrease in the stability as it contributes to slider-lubricant interactions and contamination. Disk-to-head lubricant transfer leads to lubricant pickup on the slider and also causes depletion of lubricant on the disk.

In this paper, we experimentally investigate the effect of media type, lubricant molecular weight and inclusion of X1-P and A20H on the slider-lubricant interactions using a half-delubed disk. Based on the experimental results and following analysis, we conclude that there exists a critical head-disk clearance above which there is negligible slider-lubricant interaction. The interaction starts at this critical clearance (CC) and increases in intensity as the head-disk clearance is further decreased below the CC, which depends on various HDI parameters. Comparison of CC on CHx and CHxNy media indicated that presence of nitrogen is better for HDI as it reduces the CC. The CC was found to increase with increasing lubricant molecular weight and in presence of additives X-1P and A20H. Fixed clearance experiments suggest that two different mechanisms dominate the disk-to-head and head-to-disk lubricant transfer.

Introduction:

In a Hard Disk Drive (HDD), there exist multiple layers on the magnetic disk. On top of the magnetic layer there is a hard diamond-like carbon (DLC) overcoat of about 1-2nm to protect the magnetic layer against head crashes and corrosion. On top of the DLC, there exists a molecularly thin (~0.5-1.5nm) lubricant layer to reduce the friction and wear at the head-disk interface (HDI).

In order to achieve the areal recording density of 1 Tb/in^2 and beyond, the head-disk spacing has to be reduced to below 2.5 nm. At such a small spacing, a variety of proximity interactions like intermolecular forces and electrostatic forces affect the ability of the slider to fly stably over the disk [1-2]. Lubricant pickup by the slider also reduces the stability of the slider substantially [3] and also contributes to ABS contamination. During the long operation time of the drive, this might become the most important factor affecting stability. The lubricant pickup is predominantly caused by disk-to-head lubricant transfer, which also causes lubricant depletion on the disk. Retention of lubricant on the disk as well as reduction of lubricant pickup on the slider are critical for HDI reliability and hence it is important to study disk-to-head lubricant transfer and its dependence on various parameters.

In the lubricant layer on the disk, part of the lubricant is bonded while the remaining is mobile. The bonded fraction helps in providing a permanent cover on the DLC to reduce friction and corrosion. It also resists critical failures during occasional slider-disk contact. The mobile fraction helps in replenishment of lubricant at sites where lubricant depletion has occurred. The mobile fraction is responsible for the disk-to-head lubricant transfer, which can be reduced by reducing the mobile fraction. However, it is known that reliability of the HDI is greatly reduced by reduction in the mobile fraction and fails immediately in absence of any mobile fraction.

Ma et. al. [4] showed that negative pressure sliders demonstrate disk-to-head lubricant transfer using a half-delubed disk approach. Marchon et. al. [5] proposed a model based on the langmuir equation of evaporation-condensation incorporating the airbearing shear force and studied the dependence of disk-to-head lubricant transfer on lubricant thickness and molecular weight. Smallen et. al. [6] experimentally studied the dependence of disk-to-head lubricant transfer on the lubricant disjoining pressure. They used the area of lubricant pickup by the slider as a metric for the amount of disk-to-head lubricant transfer can concluded that the amount of lubricant pickup depends on the disjoining pressure and its slope. Since this method does not give the actual volume of transfer (some lubricant may also be sheared off behind the ABS, which is not accounted for) as well as an insight into the dynamics of transfer, a half delubed disk method was used to study disk-to-head lubricant transfer and is described in detail in [7]. When a slider is flown on a half delubed disk, the disk-to-head lubricant transfer occurs in the lubed zone, while head-to-disk lubricant transfer happens in the delubed zone. By calculating volume of lubricant lost/gained by the lubed/delubed zone over time, the disk-to-head lubricant transfer can be studied. The disk-to-head lubricant transfer depends on various HDI parameters. In this report, we describe the experimental investigation of disk-to-head lubricant transfer and its dependence on three factors: media type (CHx, CHxNy), lubricant molecular weight and inclusion of additives (X1-P, A20H).

Experimental:

The experimental setup is described in detail previously [7,8]. The experiments were conducted in-situ on a Candela Optical Surface Analyzer (OSA) equipped with an ellipsometer to measure the change in the disk lubricant with a sub-Å accuracy. A sensitive acoustic emission (AE) sensor was mounted near the suspension base plate to monitor head-disk contact. In addition, a Polytec Laser Doppler Vibrometer (LDV) was focused on the slider to monitor its dynamics, which also provided an additional method of detecting contact. Very good correlation was observed in the AE and LDV contact detection. Two slider ABS designs shown in Figure 1 were used for the experiments.

A. Determination of Critical Clerance [8]:

The experimental procedure was as follows. The disk was mounted on the OSA spinstand and spun at a high rpm (17K), and then the slider was loaded onto a track and moved to a different fresh track. The disk rpm was maintained for a certain period and then reduced by increments of 1000 rpm till 11000 rpm, after which it was reduced by 500 rpm increments till 9000 rpm followed by 100-200 rpm reductions until substantial slider-lubricant interaction was observed. The rpm was further reduced until the AE and LDV detected head-disk contact to determine the touchdown rpm/velocity. There was no change in the lubricant at high rpms even when the tests were monitored for a long time as seen in Figure 2(a-d). Only when the rpm was reduced to a particular value did it show some change such as depletion and modulation (Figure 2(e)). This rpm/velocity is referred to as the critical velocity. The associated head-disk clearance determined from the difference between the critical and the touchdown velocity is the critical clearance.

It is shown in [8] that the shear force and maximum shear rate actually decreases with decreasing disk rpm/velocity and the increase in the slider-lubricant interaction can be attributed to increase in intermolecular forces as well as higher probability of 'light' contacts which might not be detected by AE/LDV.

B. Determination of lube volume depleted and transferred [7]:

During experiments, when sliders were flown on a half delubed disk, time history of lubricant profiles was obtained from Candela OSA. This was further processed to obtain quantitative estimate of the amount of lubricant depleted from the lubed zone and the amount transferred to the delubed zone. The steps in the post-processing carried out in Matlab are outlined in detail in [7]. After background subtraction and radial averaging in the lubed and the delubed zones, the resulting data was smoothed and the area under the profile corresponding to depletion or transfer was calculated. Using calibration constant of the lubricant and the radius of the track, the area calculated was converted into lubricant volume. Errors in volume calculations exist in this procedure due to noisy data, radial averaging and post-processing. Though the errors due to prior two cannot be estimated, the errors due to post-processing were determined by repeatedly calculating the lubricant volume from the lubricant profile for a few data points. The error (6σ) in post-processing was less than $500\mu m^3$ (10%) for data above $5000\mu m^3$ and decreased to about $200\mu m^3$ (20%) for data close to $1000\mu m^3$.

Tests A and B were conducted for three different sets of experiments:

(a) Dependence on Media type:

In these tests, disks from different sources were used. Various properties of these media are shown in Table 1. Media A had a glass substrate, 3.0 nm CHx (hydrogenated) type of overcoat and 1.7 nm of Zdol 4000 lubricant (1.2 nm mobile). Media B had an AlMg substrate, 2.7 nm of CHxNy (hydrogenated and nitrogenated) type of overcoat with x:y = 1:1.4, and 1.6 nm of Zdol 4000 lubricant (1.2 nm mobile). The disk topography and the measured slider dynamics over these media are shown in Figure 3. It is seen that media A has a better microwaviness control while media B has a better roughness control. The flyability of slider used (Femto A) was better for media B as the media topography features did not excite the ABS modes as much as media A. However, due to better microwaviness control on media A, the fly height modulation (3σ) was lesser in case of media A. The touchdown height was determined as ~ 3.2 nm for both media, while the glide height of media B was better than media A. However, since the experimental tracks did not contain any asperities (no AE or LDV contact detection due to asperities), the touchdown rpm/velocity is assumed to be corresponding to the touchdown height.

(b) Dependence on Lubricant Molecular Weight:

In these tests, media B was used with different molecular weight of Zdol (2000, 3500, 5700 and 10000) with thicknesses as shown in Table 2. All properties of the disks expect the lubricant molecular weight were considered same as the disks were manufactured in the same batch.

(c) Dependence on Additives:

In these tests, media B was used with different lubricants as shown in Table 3. The structure of Zdol, X1-P and A20H are shown in Table 4. For disk B1, Zdol with chain length 2000 was used. For disk B2, Zdol 2000 mixed with X1-P of molecular weight 1000 with thickness 0.6 nm was used. For disk B3, A20H 3000 – a product of Zdol 2000 and X1-P 1000 was used. It is noted that both additives (X1-P and A20H) contain cyclophophazene molecule as shown in Table 1Table 4.

Results and Discussion:

(a) Dependence on media type:

Figure 4(a) and (b) show the lubricant depletion volume after 5 minutes at each rpm when a slider (Femto A) was flown over media A and B at a radius of 26 mm, respectively, using a bar plot. The RMS AE signal is also plotted along with the depletion volume. From these figures, it is seen that the rate of lubricant depletion is high for media A as compared to media B. Also, the lubricant depletion takes place on media A at higher rpms when none or very little depletion takes place in case of media B. We clearly see a drastic transition to a high depletion rate at 10600 rpm (critical rpm) for media B. The critical rpm for media A is much higher at 15000 rpm. Since there is significant lube depletion at the critical rpm, lube volume was not measured below the critical rpm, but is expected to be increase with decreasing rpm and spacing. Further, the corresponding AE signal shows no change at the critical rpm for both the media, indicating no contact of the slider with the disk at that rpm. The slider dynamics monitored by LDV showed no change in amplitude or frequency content at various rpms until there was slider-disk contact, which was also detected by AE at 9200 rpm. From simulations, flying attitude of the slider was found and adjusted based on the fact that experimentally observed touchdown rpm (9200 rpm) corresponds to the disk touchdown height 3.5 nm. From this corrected fly height diagram shown in Figure 5, the critical clearance for media A and B was determined as 3.5 nm and 1 nm, respectively. Given that the fly height characteristics of the slider used were similar for both the media, the difference in the lubricant performance can be attributed to the difference in the lubricant – carbon chemistry in case of both the media.

Rich literature exists on the lubricant-carbon chemistry. Research on CHx and CNx overcoats [9] suggests that the inclusion of nitrogen leads up to 50% less surface coverage of lubricant. The main reason for this is the repulsion of the basic acetal backbone of the PFPE lubricant by nitrogen moieties present in the carbon surface. This repulsion keeps the lubricant backbone away from the carbon surface thus exposing more active sites on carbon. Thus, more Zdol endgroups bond to the carbon leading to better lube-carbon adhesion and also a possibility of better entanglement of lubricant molecules on CNx as the lubricant backbones are bent and endgroups of more chains try to adhere to the active sites. This increases the lubricant retention on disk surface. By comparison, the lubricant chains lie flat in case of CHx [10]. Due to these factors, the lubricant mobility is lower [11] and lubricant monolayer thickness is higher [9] for CNx than for CHx.

Various forces are exerted by the slider on the lubricant. These forces are the positive and negative pressure, shear and intermolecular forces as shown in Figure 6(a). The lubricant depletion due to slider occurs when these forces exceed the retention forces on the lubricant, which are adhesion to carbon overcoat, cohesion between lubricant molecules and IMF from substrate. Previous research noted above indicates that there is better lubricant adhesion and cohesion in presence of nitrogen in case of CHxNy. The IMF from substrate is estimated to be similar for both cases as the underlying magnetic layer (thickness > 5nm) is assumed to have similar material characteristics. The substrate materials glass and AlMg are more than 7-8 nm away from the lubricant and do not have a strong influence on the IMF on lubricant due to the substrate.

Thus, the above theory explains why in presence of similar airbearing forces, there will be more lubricant depletion as well as a higher critical clearance for CHx compared to CHxNy as observed in Figure 5.

(b) Dependence on lubricant molecular weight:

Figure 7 shows the dependence of critical clearance on the lubricant molecular weight. Experiments 1 and 2 correspond to two different sliders of design Femto B while the error bars show 3σ of the standard deviation of three experiments conducted with each slider-disk combination for determination of critical clearance. We note that standard deviations associated with expt. 1 are smaller than expt. 2. The trend from expt. 1 suggests that the critical clearance monotonically increases with lubricant molecular weight, while expt. 2 suggests that critical clearance increases initially with lubricant molecular weight, achieves a maximum and the decreases. However, due to higher standard deviations for expt. 2, the trend in expt. 1 is believed to be true.

We review past literature to explain the observed trend. Many studies have been done on the dependence of lubricant properties on its molecular weight. With increasing molecular weight, the activation energy [12] and viscosity of lubricant increase, while the lubricant mobility decreases [13]. Thus, lower molecular weight increases the rate of recovery but increases lubricant loss due to evaporation. The lower viscosity associated with lower molecular weight also decreases the shear at the interface during head-disk sliding [13]. Khurshudov et. al. [14] report a higher touchdown velocity for higher molecular weight. They attribute this to the greater "molecular roughness" of longer molecules as shown in Figure 8. The backbone of lubricant molecule is coiled and its endgroups adhere to carbon layer. Further, in presence of nitrogen in the carbon overcoat, the basic lubricant backbone is repelled. Due to this, the molecular roughness may be pronounced. Also, the endgroup density and hence the "bond density" is lower for higher molecular weight, which may reduce its adhesion with the carbon layer.

Higher molecular roughness and lower adhesion for higher molecular weight can explain the observed experimental trend in Figure 7. When the slider flies close to the disk, higher molecular roughness implies more IMF between the slider and the molecular roughness peaks. This roughness also provides a greater normal area to the airbearing shear. This combined with lesser lubricant-carbon adhesion implies that the higher molecular weight lubricant is affected more by a slider at proximity. This explains why the critical clearance is higher for higher molecular weight.

Following the experiments to determine the dependence of critical clearance on lubricant molecular weight, experiments were conducted to determine the volume of lubricant depletion and transfer [7] over 15 minutes at a constant clearance. This clearance was chosen to be the critical clearance of Zdol 2000. Thus, for the higher molecular weights the fixed clearance chosen was below their respective critical clearances. Hence, large amount of lubricant depletion and transfer was seen. Figure 9 plots the lubricant depletion from the lubed disk region, lubricant transfer to the delubed disk region and the net lubricant depletion assumed to be equal to the amount of lubricant accumulated on the slider. From the figure, it is seen that depletion increases with the lubricant molecular weight. This is because the slider flies farther and farther below the respective critical clearances as the molecular weight increases. Thus, we see that when the head-disk clearance keeps reducing below the critical clearance of the lubricant, more and more slider-lubricant interaction takes place. We also note that lubricant transfer to the delubed side does not increase at the rate of increase in depletion. In fact, as seen in Figure 10, when the transfer volume is plotted as a percentage of the depletion volume, we see that the transfer rate actually decreases with increasing molecular weight, from about 54% for Zdol 2000 to about 18% for Zdol 10000. Due to the increasing depletion rate and decreasing transfer rate with increasing molecular weight, the net lubricant accumulation on the slider increases affecting the stability of the slider. Hence, from these trends we conclude that lower molecular weight is better for low flying heights.

The above trends depletion and transfer give an insight into the physics of slider-lubricant interactions. Lubricant depletion on the lubed part of the disk is caused by disk-to-head lubricant transfer where as lubricant transfer to the delubed part of the disk is caused by head-to-disk lubricant transfer. The lubricant on the disk (at point A in Figure 6(a)) experiences high airbearing forces since the pads towards the trailing edge of the slider fly very close to the disk. These forces are instrumental in disk-to-head lubricant transfer. Majority of this lubricant transferred to the slider resides in the deep etches as suggested from ABS photographs after the experiments. It either gets transferred directly from the disk to the deep etches owing to the sub-ambient pressure created by ABS or is sheared off to the deep etches from ABS pads due to higher airbearing shear on the pads, since they fly closer to the disk. Thus, the airbearing forces acting on the lubricant transferred to the slider (at point B in Figure 6(b)) are much weaker since the deep etches are much farther from the disk. Hence, the head-to-disk lubricant transfer is mainly governed by the inherent lubricant properties such as its desorption or evaporation energy rather than the airbearing forces. With increasing molecular weight, the desorption energy also increases [13]. This explains why the head-to-disk transfer rate decreases with increasing molecular weight.

From the above analysis, we concluded that the governing mechanisms of disk-to-head and head-to-disk lubricant transfer are different. The disk-to-head lubricant transfer is mainly influenced by airbearing forces and lubricant properties like molecular roughness and cohesion because they have an influence on the magnitude of airbearing forces acting on the lubricant. By contrast, the head-to-disk lubricant transfer is mainly governed by the inherent lubricant properties such as its desorption or evaporation energy rather than the airbearing forces.

Marchon et. al. [5] developed a model of lubricant transfer based on evaporation-condensation of lubricant, which does not consider the effect of airbearing forces. According to this model, the lubricant condensation flux R_{cond} from disk-to-head is given by

$$R_{cond} = P_0 \sqrt{\frac{M_n}{2\pi RT}} \cdot \exp\left(-\frac{\pi(t_d) M_n}{\rho RT} \right) \qquad (1)$$

where P_0 is the bulk vapor pressure, M_n is the molecular weight, R is the gas constant, T is the absolute temperature, and ρ is the lubricant density. $\Pi(t_d)$ is the disjoining pressure for the disk lubricant thickness t_d. From R_{cond}, the volume flux of lubricant from disk-to-head or can be calculated as $Q_{cond} = R_{cond} A/\rho$, where A is the cross-section area and ρ is the lubricant density. Similarly, the evaporation flux R_{evap} of lubricant from head-to-disk can be calculated from equation (1) by replacing t_d by t_s, the slider lubricant thickness. As is seen from equation (1), this model predicts an exponential decrease in the transfer rate with increasing molecular weight given same lubricant volume or thickness on the slider and can thus explain the transfer rate trend in Figure 10. Thus, we have an experimental verification of this model and also supports the current argument that head-to-disk lubricant transfer is mainly influenced by lubricant evaporation energy rather than the airbearing forces.

The above model, however, does not explain the trend of disk-to-head lubricant transfer manifesting as lubricant depletion on the disk. This is because the airbearing forces influence the disk-to-head lubricant transfer more than lubricant evaporation energy. Thus, a disk-to-head lubricant transfer model based on airbearing forces, lubricant molecular roughness, cohesion and adhesion energy needs to be developed based on the current experimental data. Such a model will also be able to estimate the influence of all the airbearing forces as well as lubricant and media type on the disk-to-head lubricant transfer.

(c) Dependence on additives:

Additives are added in the lubricant because they can enhance the tribological performance and thus the reliability of the head-disk interface. X-1P is the most commonly used additive as it possesses excellent lubricity, low vapor pressure, high thermal stability and good solubility in non-CFC solvents [13]. In addition, Chen et. al. [13] also found that X-1P, when used as an additive, prevents catalytic degradation of lubricant as well as improves the lubricant mobility thereby improving the overall tribological performance. It has been noted in [13] that previous researchers proved through ESCA measurements that X-1P forms an underlayer in case of Zdol lubricant. The chemical structure of X-1P is shown in Table 4. It contains cyclophosphazene molecule which is large in size compared to the Zdol chain with a radius of gyration of 5Å. Therefore, it could add to the molecular roughness of the lubricant when used as an additive. Further, from higher mobility of AM3001 lubricant in presence of X-1P, Chen et. al. [13] "believe(d) that X1-P molecules preferably occupied the bonding sites on the carbon surface," thereby reducing the bonding fraction and adhesion of Zdol molecules with the carbon surface.

A20H is obtained when X1-P is chemically reacted with Zdol. The resultant chemical structure of A20H is shown in Table 4. One endgroup for A20H is the –OH group (from Zdol) while the other is the cyclophosphazene. Similar to X-1P, A20H is predicted to have more molecular roughness than Zdol to the cyclophosphazene moiety. Waltman et. al. [15] report a lower mobility for A20H as compared to Zdol with comparable molecular weight. Their further analysis indicates that there is actually an increased adhesion provided by adsorbed film structure of A20H on the carbon surface.

Figure 11 shows the measured critical clearance for Femto B slider for Zdol, Zdol+X-1P and A20H lubricated disks with lubricant thicknesses as shown in Table 4. It is seen that the critical clearance is more for Zdol+X-1P mixture and A20H as compared to Zdol. This increase in the critical clearance can be attributed mainly to increased molecular roughness due to the cyclophosphazene moiety present in X-1P and A20H.

Following the experiments to determine the dependence of critical clearance on inclusion of additives, experiments were conducted to determine the volume of lubricant depletion and transfer over 15 minutes at a constant clearance. The results of these experiments are shown in Figure 12. First set of experiments were done maintaining the head-disk clearance at 1.5 nm, which is above the critical clearance of Zdol, but below the critical clearances of Zdol+X-1P and A20H. Hence, no lubricant depletion and transfer was seen for Zdol. However, comparable amounts of depletion and transfer were seen for Zdol+X-1P and A20H. For the second set of experiments, the head-disk clearance was decreased to about 0.7 nm by reducing the disk rpm/velocity. In this case, the clearance was just below the critical clearance for Zdol, but much below that for Zdol+X-1P and A20H. Hence, some depletion and transfer was observed in case of Zdol in this case while much more depletion and transfer was observed in case of Zdol+X-1P and A20H as compared to the first set of experiments. From Figure 12, we also see that much more depletion and transfer is seen in case of Zdol+X-1P as compared to A20H even if the critical clearances are similar for both the cases. This is attributed to the different lubricant adhesion. As mentioned before, previous research concluded that X-1P tends to form an underlayer for Zdol and preferentially binds to active sites in carbon resulting in lower lubricant-carbon adhesion and hence, increased lubricant mobility. By contrast, A20H is reported to have decreased mobility as compared to Zdol due to better lubricant-carbon adhesion. Thus, due to poorer adhesion, there is more lubricant depletion and transfer in case of Zdol+X-1P as compared to A20H.

From the above results, we conclude that negligible slider-lubricant interaction takes place when the head-disk clearance is above the critical clearance; the interaction starts at the critical clearance and keeps increasing as the head-disk clearance keeps reducing below the critical clearance. Further, the critical clearance seems to depend on lubricant molecular roughness more than the lubricant-carbon adhesion, which seems to influence the intensity of slider-lubricant interaction below the critical clearance. However, more experimental data regarding this is needed to validate this conclusion.

Conclusions:

In this paper, we experimentally investigated the effect of media type, lubricant molecular weight and inclusion of X1-P and A20H on the slider-lubricant interactions using a half-delubed disk. Based on the experimental results and following analysis, we conclude that:

(a) There exists a critical head-disk clearance above which there is negligible slider-lubricant interaction. The interaction starts at this critical clearance (CC) and increases in intensity as the head-disk clearance is further decreased below the CC, which depends on various HDI parameters.

(b) Media-type: Comparison of CC on CHx and CHxNy media indicated that presence of nitrogen is better for HDI as it reduces the CC primarily due to better lubricant-carbon adhesion and possibly better entanglement of lubricant chains. Further, the contribution of disk microwaviness to the slider-lubricant interaction needs to be examined as it affects slider flyability.

(c) Lubricant Molecular Weight: The CC was found to increase with increasing lubricant molecular weight for Zdol. This is attributed to the increased molecular roughness and lower bond density at higher molecular weights. Fixed clearance experiments revealed that different mechanisms dominate disk-to-head and head-to-disk lubricant transfer. Airbearing forces seem to dominate the disk-to-head lubricant transfer while inherent lubricant properties such as evaporation energy seem to dominate head-to-disk lubricant transfer.

(d) Additives: The CC was found to increase in presence of additives X-1P and A20H. This is mainly attributed to increase in the lubricant molecular roughness due to the presence of large cyclophosphazene molecule. Fixed clearance experiments suggested that lubricant-carbon adhesion significantly influences the amount of lubricant depletion and transfer when head-disk clearance is below the CC.

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References:

[1] R.P. Ambekar, V.Gupta and D.B. Bogy, “Experimental and numerical investigation of the dynamic instability in the head-disk interface at proximity,” *ASME J. Tribol.*, vol. 127, no. 3, pp. 530-36, July 2005.

[2] V. Gupta and D.B. Bogy, “Dynamics of sub-5-nm air-bearing sliders in the presence of electrostatic and intermolecular forces at the head-disk interface,” *IEEE Trans. Magn.*, vol. 41, no. 2, pp. 610-15, Feb 2005.

[3] R.P. Ambekar and D.B. Bogy, “Effect of Slider Lubricant Pickup on Stability at the Head-Disk Interface,” *IEEE Trans. Magn.*, vol.41, no.10, pp. 3028-30, Oct. 2005.

[4] X. Ma, H. Tang, M. Stirniman and J. Gui, “Effect of Slider on Lubricant Loss and Redistribution,” *IEEE Trans. Magn,* Vol. 38, Vol. 5, 2144-46, Sept. 2002.

[5] B. Marchon, T. Karis, Q..Dai and R. Pit, “A model for lubricant flow from disk to slider,” *IEEE Trans. Magn.*, vol. 39, no. 5, pp.2447-2449, Sept. 2003.

[6] M. J. Smallen and H. W. Huang, “Effect of disjoining pressure on disk-to-head lubricant transfer,” *IEEE Trans. Magn.*, vol. 39, no. 5, pp.2495-2497, Sept. 2003.

[7] R.P. Ambekar, D.B. Bogy and C.S. Bhatia, “Lubricant Depletion and Transfer at the Head Disk Interface in Hard Disk Drives,” CML Report 2006-10 (Accepted to *ASME J. Tribol.*)

[8] R.P. Ambekar, D.B. Bogy and C.S. Bhatia, “Critical Clearance for Slider-Lubricant Interactions at the Head-Disk Interface in Hard Disk Drives,” CML Report 2007-03 (Submitted to *J. Appl. Phys.*)

[9] G.W. Tyndall, R.J. Waltman and D.J. Pocker, “Concerning the Interactions between Zdol Perfluoropolyether Lubricant and an Amorphous-Nitrogenated Carbon Surface,” *Langmuir*, vol. 14, pp. 7527-7536, 1998.

[10] R.J. Waltman, G.W. Tyndall and Pacansky, “Computer-Modeling Study of theInteractions of ZDOL with Amorphous Carbon Surfaces”, *Langmuir*, Vol. 15, pp. 6470-6483, 1999.

[11] S.K. Deoras, S-.W. Chun, G. Vurens and F.E. Talke, “Spreading and mobility analysis of PFPE lubricants using a Surface Reflectance Analyzer,” *Trib. Intl.*, Vol. 36, No. 4-6, pp. 241-246, Apr-Jun 2003.

[12] R.J. Waltman, and G.W. Tyndall, “The evaporation and bonding of ZDOL polyperfluorinated Ether lubricants on CHx carbon overcoated rigid magnetic media. 1 Effect of Molecular Weight.”, *J. Phys. Chem.*, ******

[13] C-.Y. Chen, “Tribochemistry of the Decomposition Mechanisms of Perfluoropolyether Lubricants at the Head-Disk Interface of Hard Disk Drives in UHV,” Ph. D. Dissertation, University of California Berkeley, 1999.

[14] A. Khurshudov and R. J. Waltman, “The contribution of thin PFPE lubricants to slider–disk spacing,” *Trib. Lett.*, Vol. 11, no. 3-4, pp. 143-149, 2001.

[15] R.J. Waltman, N. Kobayashi, N. Shirai, A. Khurshudov and H. Deng, “The tribological properties of a new cyclotriphosphazene-terminated perfluoropolyether lubricant,” Trib. Lett., vol. 16, no. 1-2, pp. 151- 162, Feb. 2004.

Tables:

Properties	Media A	Media B
Substrate	Glass (39 mils)	Al-Mg (50 mils)
COC type	CHx	CHxNy
COC thickness	3.0 nm	2.7 nm
Lubricant type	Zdol 4000	Zdol 4000
Lubricant thickness	1.6 nm 0.4 nm bonded, 1.2 nm mobile	1.7 nm 0.5 nm bonded, 1.2 nm mobile

Table 1: Media properties

Disk No.	Molecular Weight (Da)	Lubricant Thickness [Mostly mobile] (nm)
ZD1	2000	1.49
ZD2	3500	1.62
ZD3	5700	1.51
ZD4	10000	1.68

Table 2: Lubricant thickness for disks corresponding to different lubricant molecular weight used in the experiments

Disk No.	Disk Type	Lubricant Thickness (nm)		
		Total	Zdol	Additive
B1	Zdol 2000	1.49	1.49	0
B2	Mixture: Zdol 2000 + X1-P 1000	1.56	1.50	0.06
B3	Product: A20H 3000 = Zdol 2000 + X1-P 1000	1.73	1.43	0.3

Table 3: Lubricant thickness for disks corresponding to different additives used in the experiments

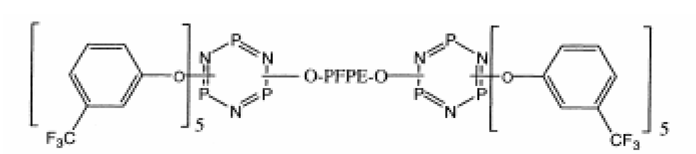
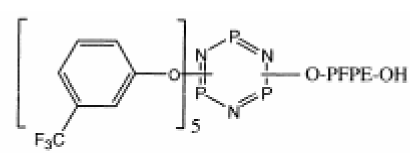
Lube Type	Structure
Zdol	$HO\text{-}CH_2CF_2[(OCF_2CF_2)_p(OCF2)_q]OCF_2CH_2\text{-}OH$
X-1P [15]	
A20H [15]	

Table 4: Chemical structures of Zdol, X-1P and A20H

Figures:

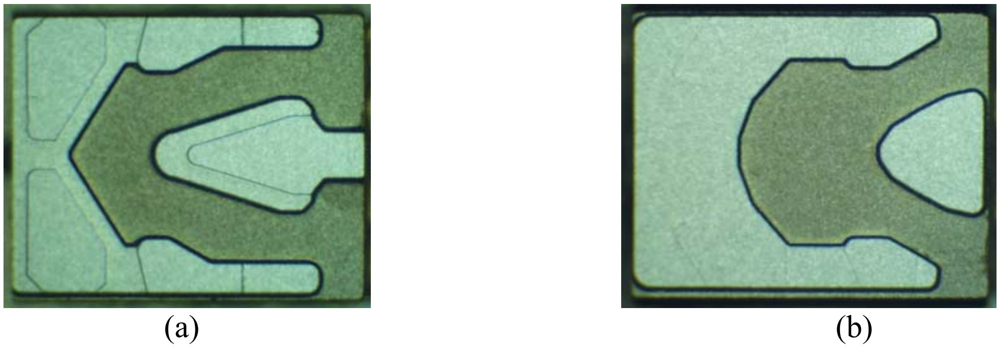


Figure 1: ABS designs used for experiments: (a) Femto A; (b) Femto B

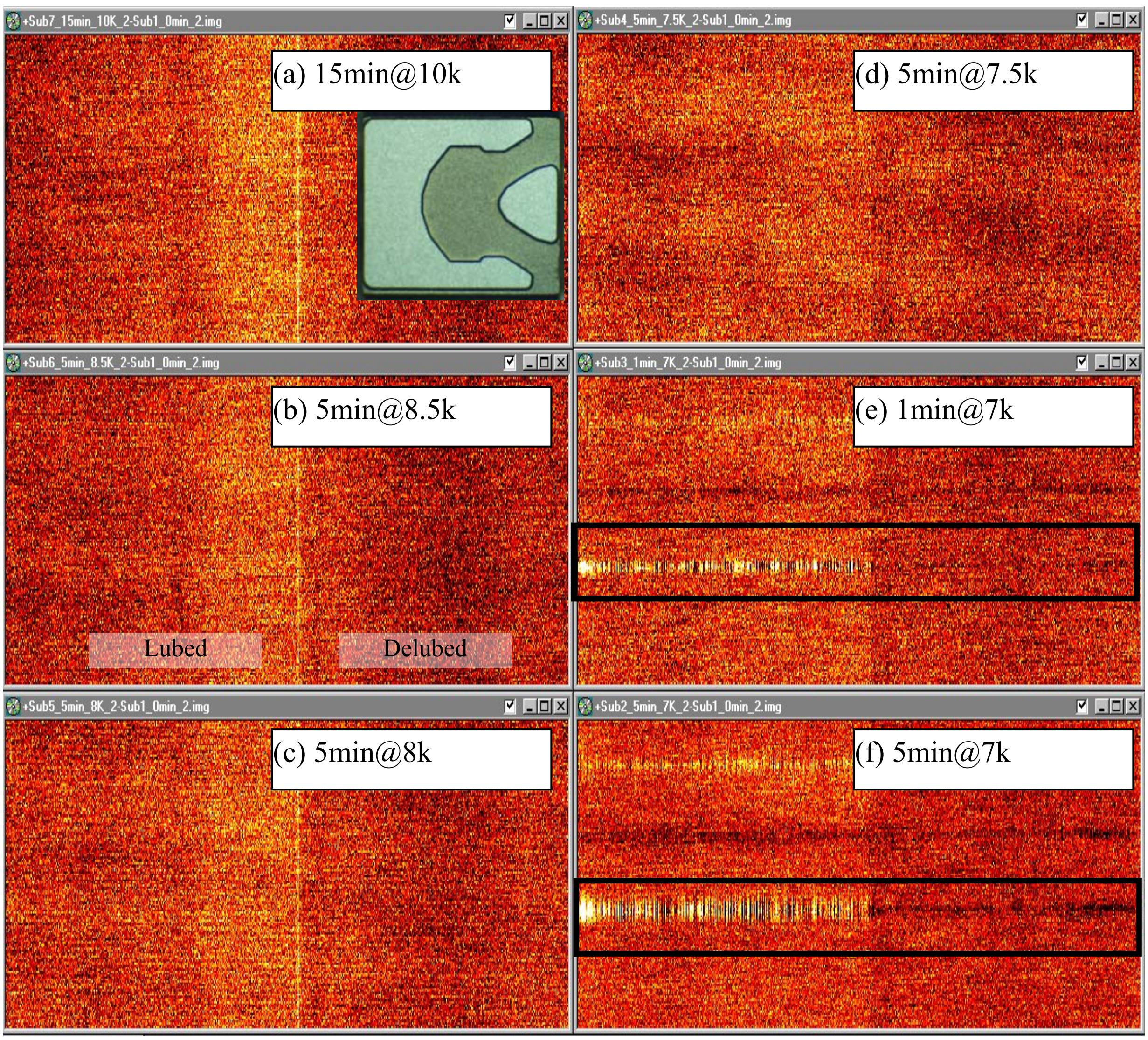
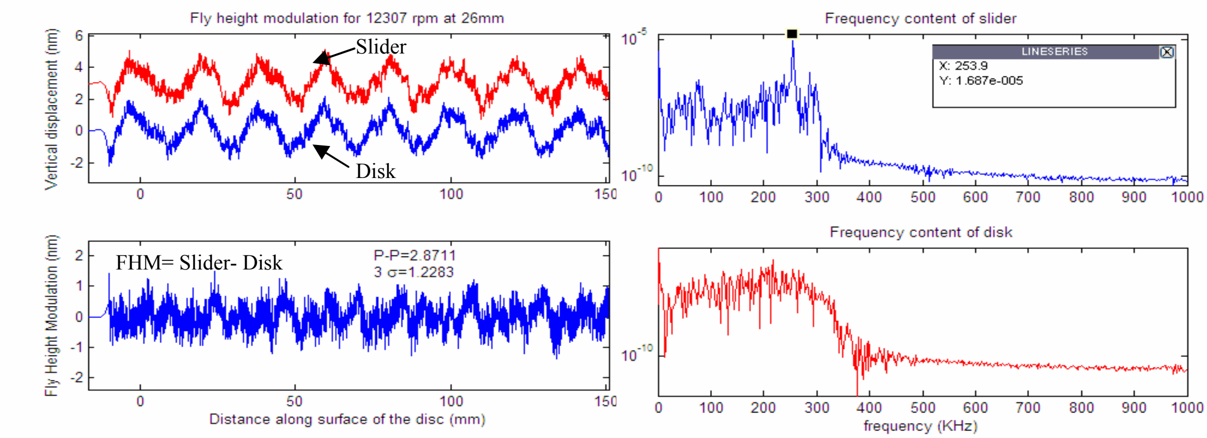
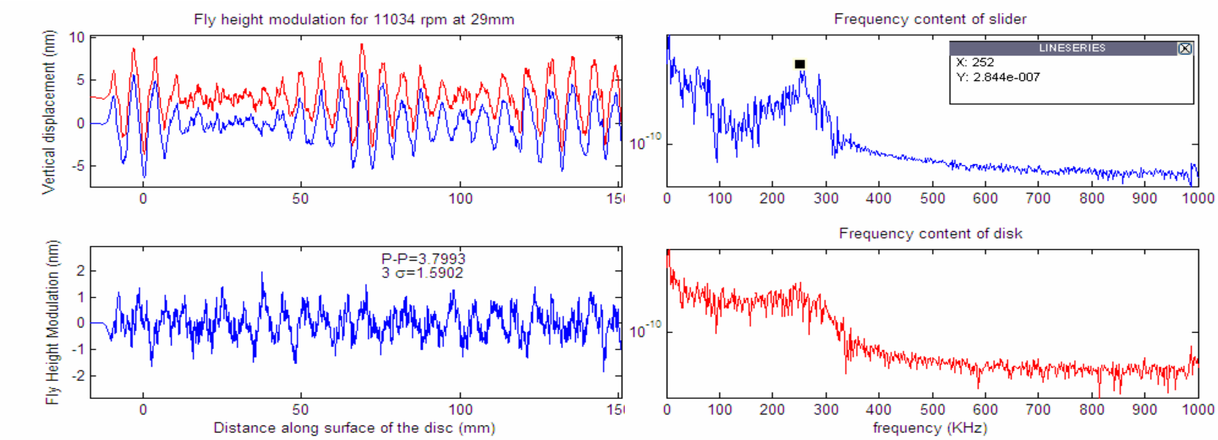


Figure 2: OSA traces to show slider-lubricant interactions at different rpms: (a-d) no interaction; (e) interaction starts at critical rpm and (f) interaction continues resulting in more depletion and transfer as time progresses

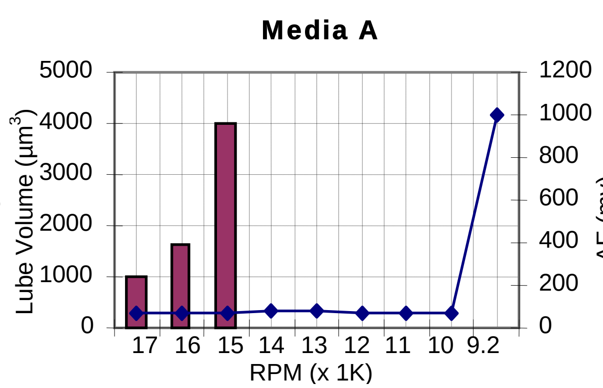


(a)

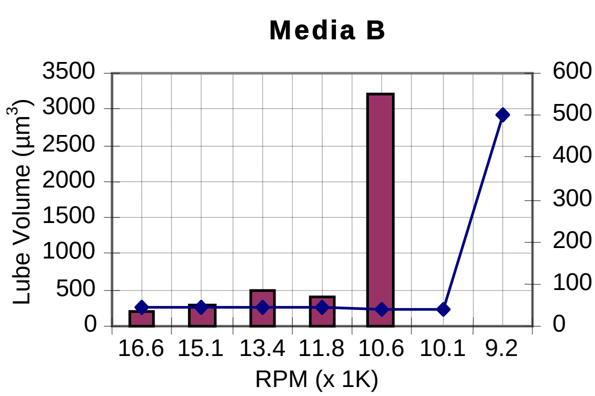


(b)

Figure 3: Slider (Femto A) response to disk topography, FHM and frequency spectra for slider and disk for (a) Media A and (b) Media B.



(a)



(b)

Figure 4: Lubricant volume depleted in 5 minutes at various rpms along with corresponding AE signal with Femto A slider for (a) Media A and (b) Media B.

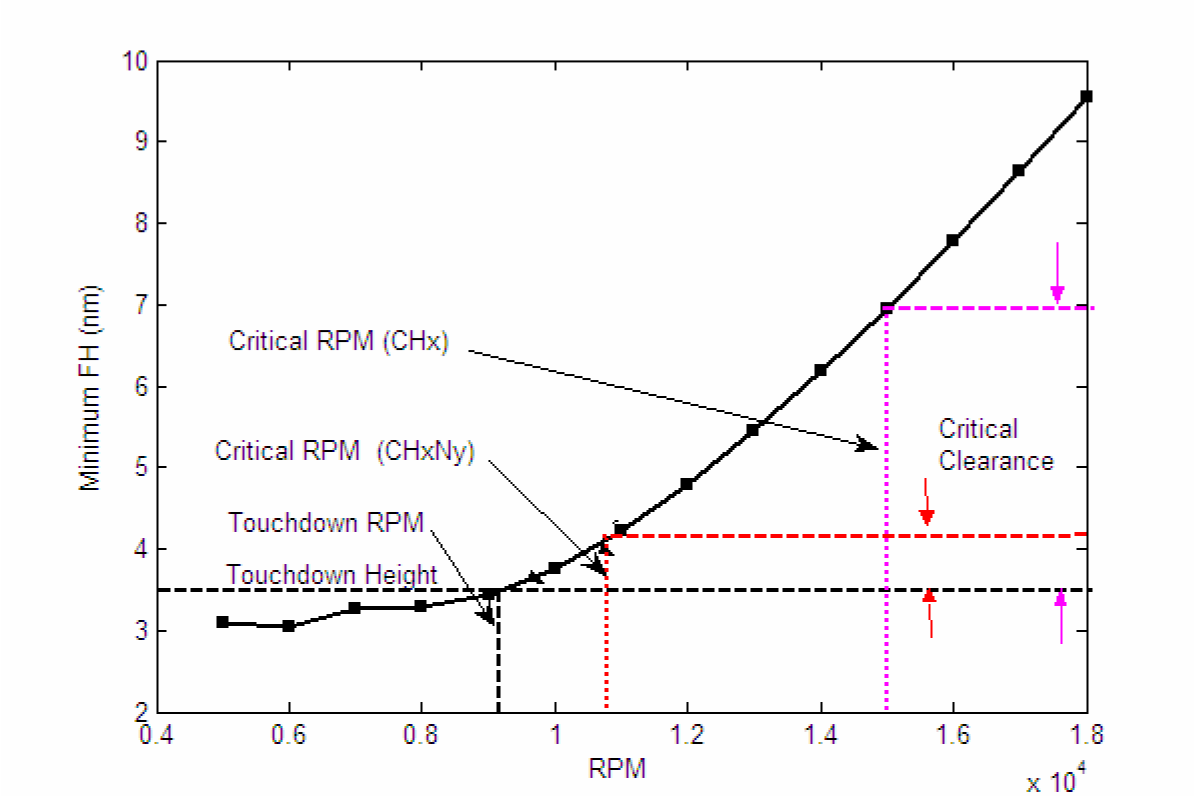


Figure 5: Determination of critical clearance from critical rpm and touchdown rpm for Media A (CHx) and Media B (CHxNy) for Femto B slider.

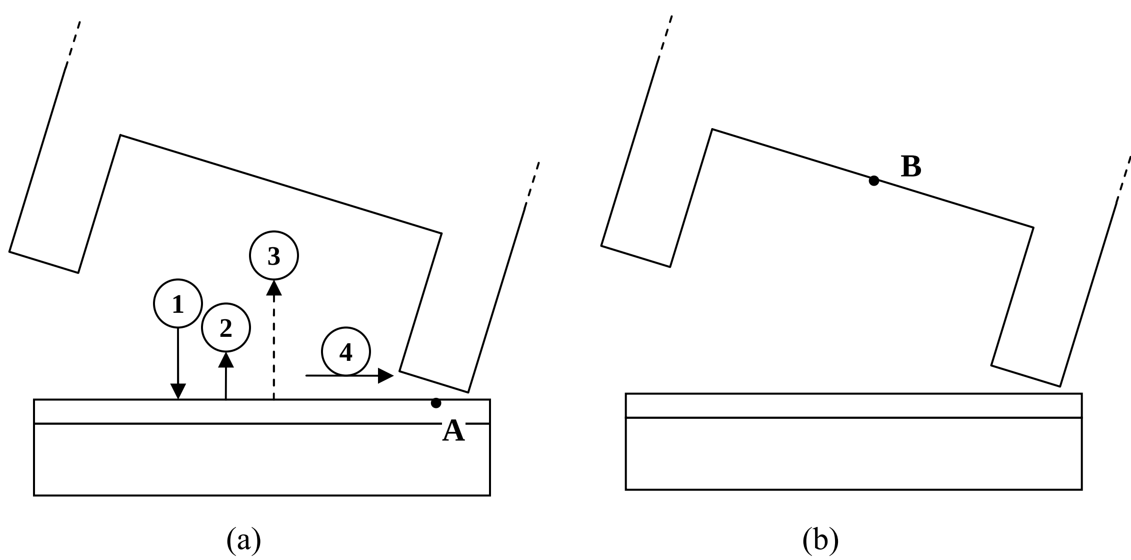


Figure 6: (a) Different airbearing forces acting on lubricant at point A on the disk: (1) Positive airbearing pressure, (2) Negative airbearing pressure, (3) Intermolecular force and (4) airbearing shear;

(b) No significant airbearing forces on lubricant placed at point B in the deep etch level on the slider.

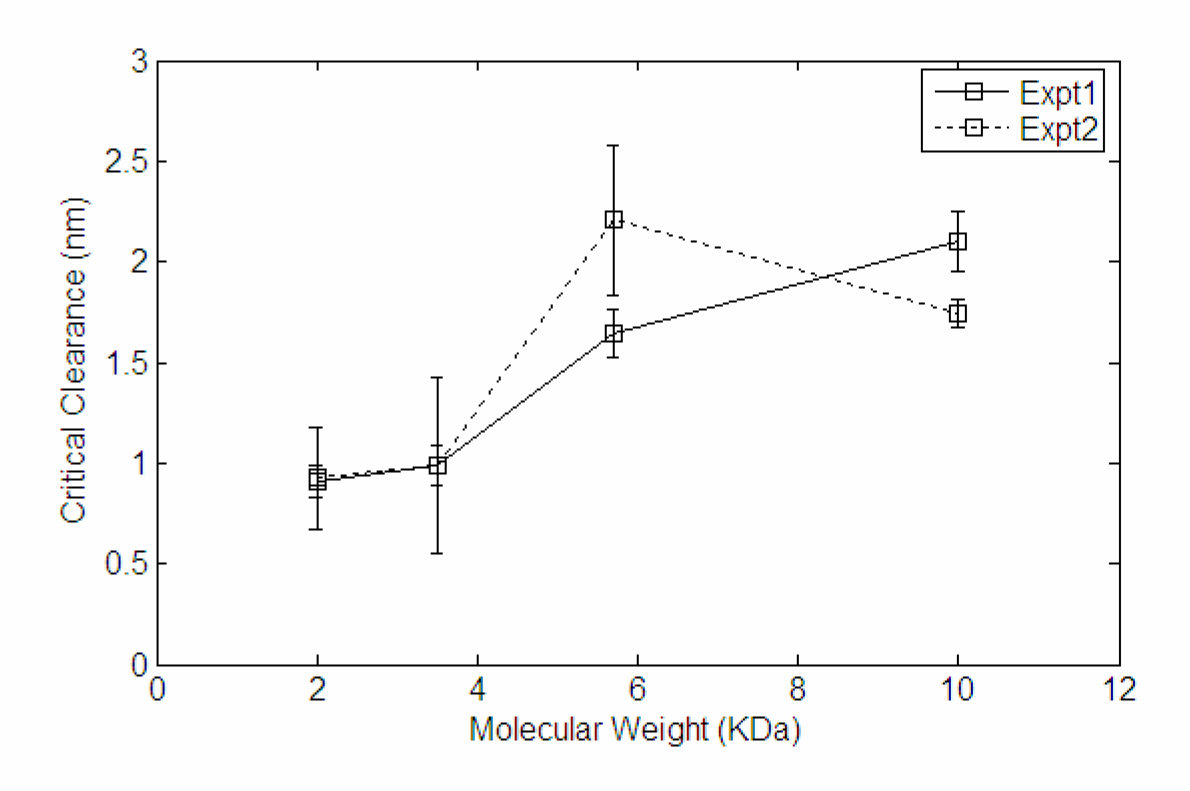


Figure 7: Dependence of critical clearance on lubricant molecular weight for Zdol for Femto B slider.

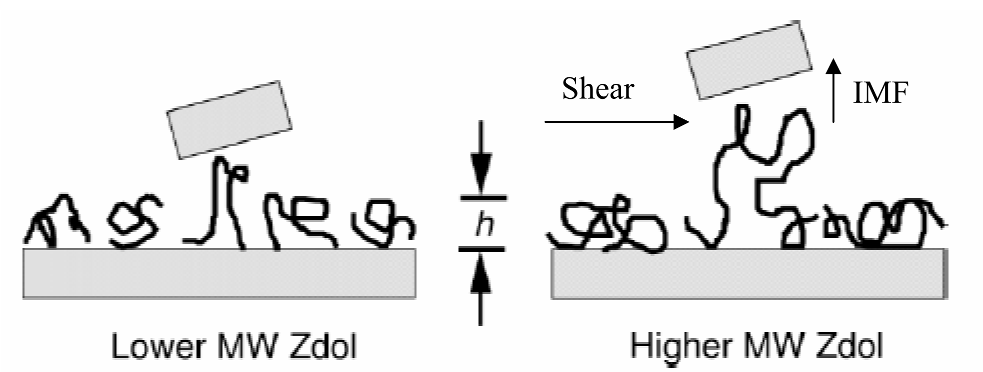


Figure 8:Depiction of molecular roughness for lower and higher lubricant molecular weights [14]. Directions of airbearing shear and intermolecular forces due to slider are also shown.

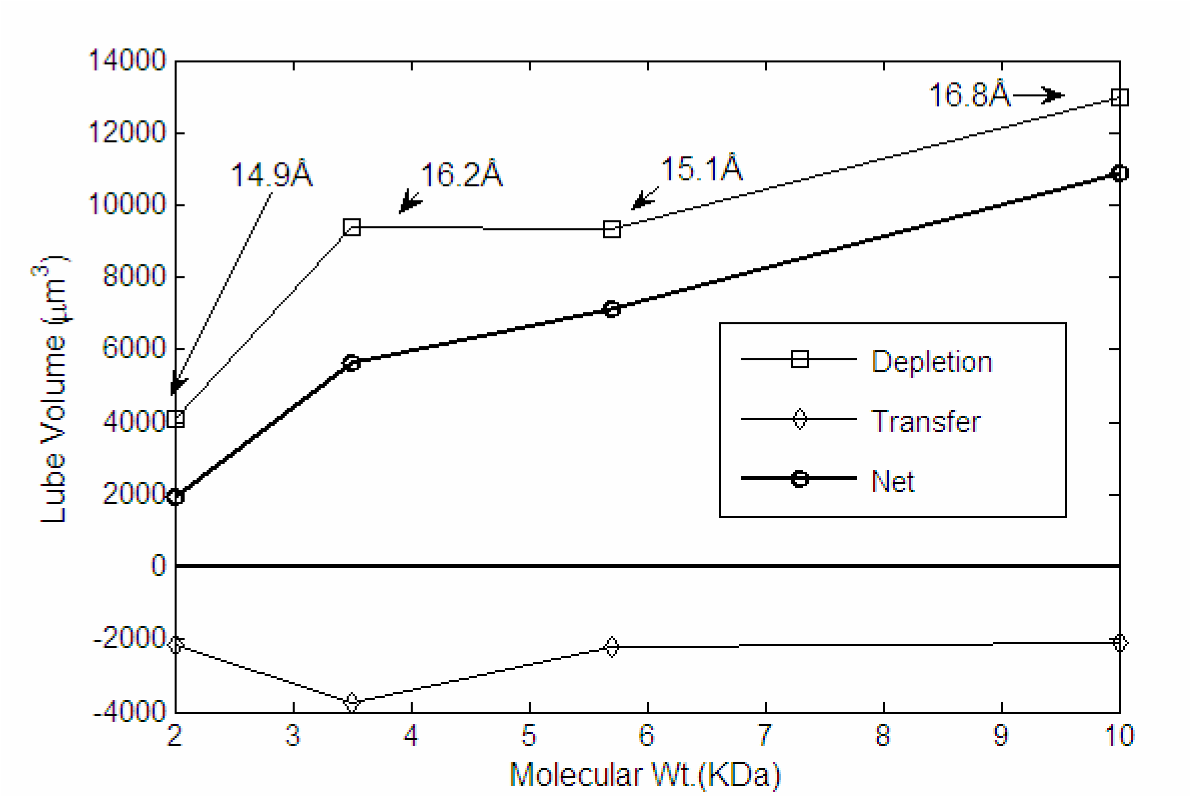


Figure 9: Fixed clearance tests: Dependence of lubricant volume depleted, transferred and the net lubricant accumulation on slider on lubricant molecular weight for Zdol with Femto B slider.

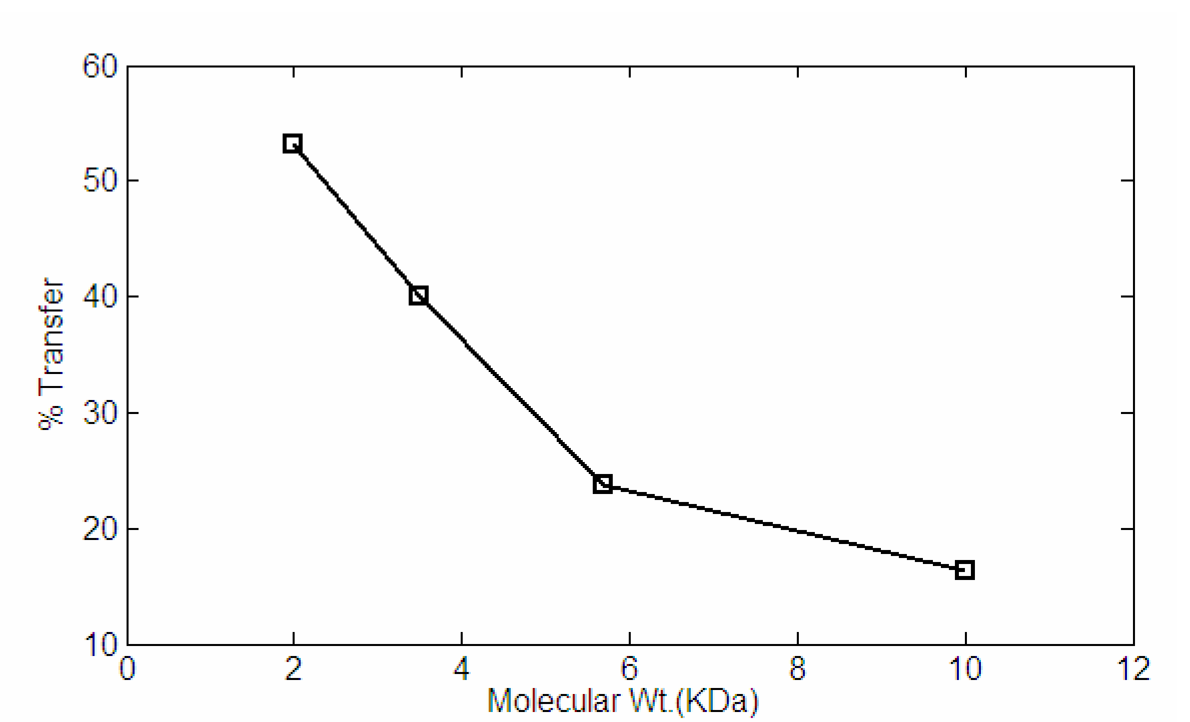


Figure 10: Lubricant transfer volume as a percentage of the lubricant depletion volume (Figure 9) for different molecular weights of Zdol for Femto B slider.

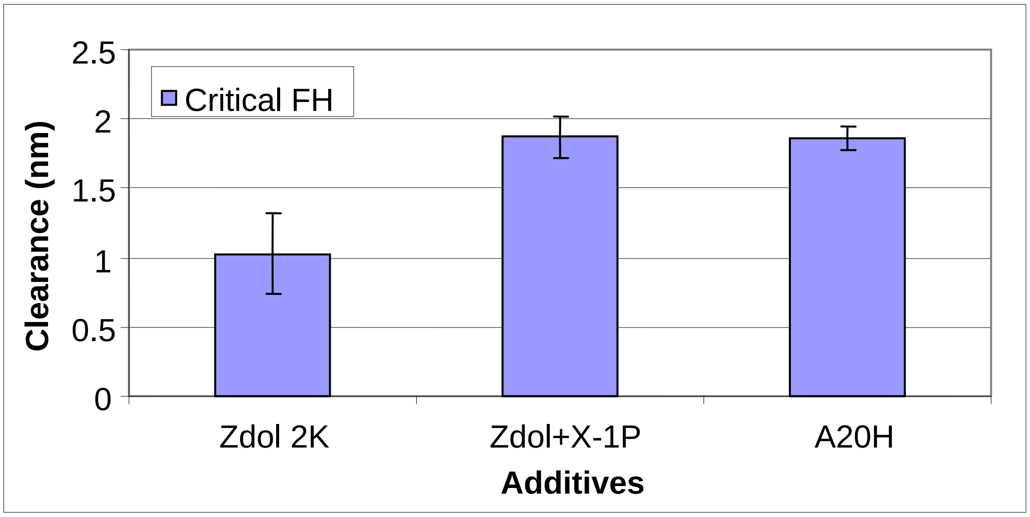


Figure 11: Dependence of critical clearance on inclusion of additives X-1P and A20H in Zdol 2000 for Femto B slider.

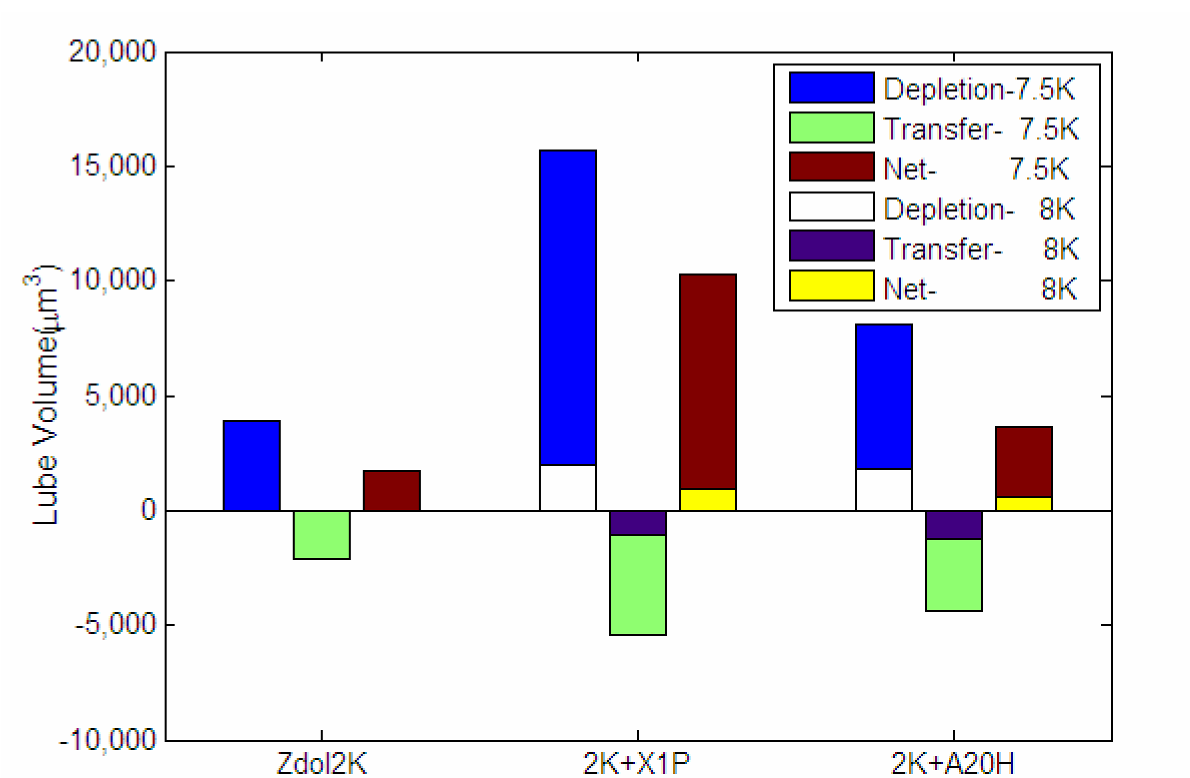


Figure 12: Fixed clearance tests: Dependence of lubricant volume depleted, transferred and the net lubricant accumulation on slider on inclusion of additives in Zdol with Femto B slider.