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WEAR

An investigation of nano-wear during contact recording

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Abstract

A method for measuring wear phenomena at the nano-scale is presented. It involves the introduction of micron sized indentations on the sliding surface which are 10–20 nm deep to act as reference for the measurement of wear. The changes in the size and depth of these indentations as a function of sliding time are monitored with an atomic force microscope. The method has been applied to measure wear on a contact recording head consisting of a diamond-like carbon wear pad of physical dimensions of 10 by 35 μm, under development for use in magnetic hard disks. Constant speed drag tests and sweep tests were conducted in the study. The wear coefficients obtained are of the order of 10^{-10}. These results correspond to a wear rate of 4.5 nm per week for constant speed drag testing and between 9 and 12 nm per week for sweep testing at a nominal load of 350–400 μN.

Keywords: Nano-wear; Contact recording; Tribology; DLC wear; Indentation method; Micro-electro-mechanical systems

1. Introduction

The study of micro- and nano-tribology has become increasingly important in recent years. An application where micro-tribology has gained attention is the head–disk interface (HDI) of a computer hard disk drive [1]. Another area of micro-tribology is the field of micro-mechanical systems where miniaturized mechanical devices are built using thin film techniques. In a number of micro-mechanical devices such as micro-gears and micro-motors [2], contact occurs between the moving parts. Since the dimensions of these devices are in microns, with tolerances in nanometers, an understanding of the tribology at the nano-level is necessary [3–5]. In both micro-mechanical devices and computer data storage devices, nano-tribology is important in evaluation of the durability of the surfaces in contact and in reducing the wear rates to increase the maximum useful life [6].

In conventional tribological investigations, a *pin-on-disk* or *cylinder-on-cylinder* type arrangement is used for friction and wear testing of different materials. Since the advent of surface probing microscopes such as the scanning tunneling microscope (STM) or the atomic force microscope (AFM), it has become possible to image atomic scale features of surfaces. The need for a better understanding of friction, adhesion and wear phenomena on a nano-scale has led to the development of new testing methods to perform scratch-type wear tests or nano-indentation tests using tips made from diamond [7–9]. These methods have led to an improved understanding of surface and tribological phenomena at the nano-scale. However, they have two limitations. The stylus material is different from the material used in real sliding situations. In addition, the shape of the contact stylus is different from the geometry of the sliding surfaces. Thus, it is difficult to use results from stylus experiments for determining the effect of surface roughness, lubricant characteristics or environmental conditions in actual tribological situations. Clearly, a direct measurement method is needed for the evaluation of the tribological performance of sliding surfaces. The present study is concerned with such an investigation of the tribology at the interface of a contact recording head and a magnetic hard disk.

A conventional magnetic hard disk assembly in a computer disk drive consists of an aluminum disk coated with an approximately 50 nm thick magnetic layer which is protected by an amorphous diamond-like carbon layer of 20–30 nm and a lubricant layer of 2–3 nm. A slider which carries the read–write element flies over the disk at a spacing of approximately 50 nm in current designs. In order to further increase the recording density, a decrease in the flying height is desired and spacings on the order of 10–15 nm are likely to be implemented in the future. In such situations contacts between the slider and the disk exist at times and wear considerations of

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the interface become increasingly more important. A different way of achieving very high recording densities is to operate the head–disk interface in continuous sliding contact with the disk surface at all times (contact recording) [10]. Since continuous contact between slider and disk causes wear of the contacting surfaces it is important to understand the tribological performance of the head–disk interface prior to implementing contact recording in actual disk drives in the field. Contact recording calls for an ultra-low wear system for reliable operation.

Evaluating the tribological performance of the HDI is crucial in the magnetic storage industry. Two standard tests that are used for testing the performance of the head/disk interface are the "constant speed drag" test and the "contact start stop" (CSS) test. Another type of test is the so-called "sweep" test. In the drag and contact start/stop tests, the slider is placed at a fixed radial position on the disk and friction, stiction, cycles to failure and slider take-off velocity are measured. In a sweep test, the arm that carries the slider oscillates to permit access to the entire surface of the disk by the slider. Although friction and stiction measurements are important in terms of torque requirements of the spindle motor and final failure of the HDI, none of these measurements relate directly to wear. Typical wear rates of contact recording sliders have been reported to be on the order of tens of nanometers per week [10]. Since the measurement of such small wear rates requires that wear tests are conducted over 10 or even 20 weeks, it is apparent that a better way for the measurement of wear rates over shorter time periods is highly desirable. The present study deals with the topic of wear measurement between a slider and a disk on the nano-scale, where wear rates on the order of several nanometers per week are encountered. The method involves the introduction of micron-sized indentations that are several tens of nanometers deep on the slider surface and the measurement of the change in dimensions of these features as a function of time using atomic force microscopy. The dependence of nano-wear on load and sliding distance is investigated and nano-wear rates are compared with macro wear rates from literature.

2. Contact recording interface

A typical contact recording set-up is shown in Fig. 1. It consists of a flexible suspension with a small recording head structure attached at one end (Microflexhead®, Censtor Corporation). The head structure, fabricated by thin film techniques consists of a magnetic element and a carbon contact wear pad. The wear pad has a footprint of approximately 10×35 μm and is about 6–10 μm in height. Fig. 2 shows photomicrographs of the top view (contact surface) and end view of the wear pad. The material of the wear pad is hydrogenated diamond-like carbon (DLC), deposited by plasma enhanced chemical vapor deposition. Fig. 3 shows the Raman spectrum of the contact wear pad with the characteristic D and G peaks for the sp^3 and sp^2 components of the material

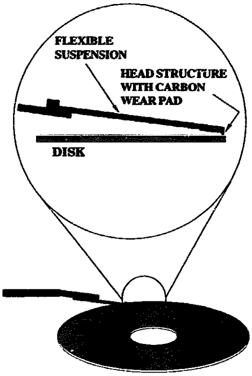

Fig. 1. Schematic diagram of suspension and contact recording head.

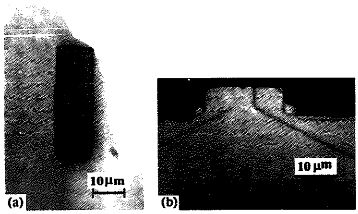

Fig. 2. Photomicrographs of: (a) top view showing the contact surface of the carbon wear pad; (b) end view of the carbon wear pad.

at 1340 and 1530 cm^{-1}, respectively. In addition, a C–H peak can be observed near 2955 cm^{-1}. The wear pad is in continuous contact with a carbon coated magnetic disk of 10 nm carbon overcoat thickness. The disk surface has an rms roughness of 0.4–0.5 nm and is lubricated with a thin layer of approximately 2 nm perfluoro polyether lubricant. The AFM images of a typical air bearing disk and a contact recording disk are shown in Fig. 4, respectively. Comparing the surface roughness of the two disks, we observe that a typical contact recording disk is substantially smoother than a typical air bearing disk.

The wear measurement of contact recording systems is made difficult because wear rates on the order of nanometers per week must be determined on a wear pad which has a total height of 6–10 μm as shown in Fig. 2(b). At present, the resolution of most optical and stylus profilers is insufficient to measure wear rates in the nanometer range over such heights. As a result, a reliable, high resolution measurement requires long testing times to observe an appreciable change

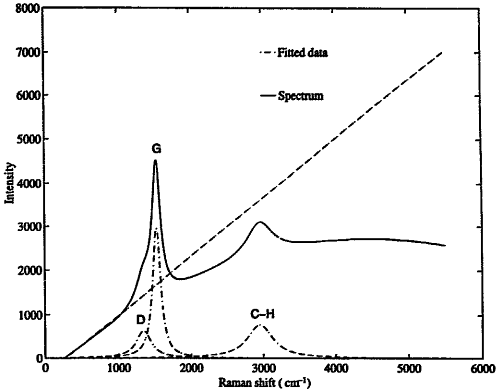

Fig. 3. Raman spectrum from the contact wear pad showing the D, G and C–H peaks.

in the total height. In addition to the limited range for the total height that can be measured, optical methods have a low spatial resolution, on the order of 1 μm. Electron microscopes have better spatial resolution. However, they require extensive sample preparation and one cannot measure heights easily. The AFM has better height and spatial resolution. However, its height range is limited to approximately 5 μm. It requires a calibration for large scans and heights.

In a previous study [10], wear of contact recording heads was observed using the so-called "tilting pad" method. In this method, the head is tilted so that only one corner of the slider touches the disk surface at the beginning of the test. After sliding is initiated, a facet is formed, starting at the corner of the wear pad surface that is in contact with the disk. The dimensions of the facet are used to determine the wear volume. The growth of the facet is slow and hence the tilting pad method requires long testing times.

3. Experimental procedure for measurement of nano-wear

In order to measure wear of contact recording sliders, we introduced pyramid-shaped indentations on the slider wear surface to act as reference for subsequent wear measurements. The depth of the indentations was of the order of tens of nanometers, while the length of the indentations was several microns. The change in the dimensions of the indentations was monitored as a function of sliding time using an atomic force microscope. Since the indentation area was small compared with the area of the wear pad, the slider dynamics and the tribological performance of the interface was not affected by the indentations. Different indentation depths can be

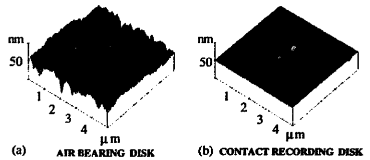

Fig. 4. AFM images of (a) conventional air bearing disk, and (b) contact recording disk.

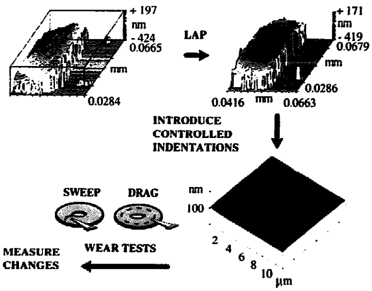

Fig. 5. Test procedure for wear measurement using nano-indentations.

obtained by varying the indentation load. A typical indentation load used was 25 mN.

Fig. 5 shows the experimental procedure followed for measuring wear on the contact wear pad. At first, the wear

Table 1
Summary of experimental measurements

Test no.	Mode	Velocity (m s^{-1})	Load (μN)	Area (μm^2)	Time (h)	Wear depth (nm)	Wear vol. (μm^3)
1	Drag	7.84	343	468	162	5.22	2.08
2	Drag	7.5	310	450	821.75	19.9 (max)	8.95
3	Sweep	–	1617	456	72	>25	11.4
4	Drag	7.48	370	468	214	7.25	3.39
5	Sweep	–	436	760	72	4	3.04
6	Sweep	–	620.5	340	40	16.2	5.41
			620.5	340	129	21.1	7.13
			620.5	340	165	26.7	9.08

pad was lapped down on a lapping disk to obtain a flat surface. Then, indentations were made on the wear surface using a low load micro-hardness tester (DM400 LF, Leco Corporation) and a diamond Knoop indentor. After this, the surface profiles of the indentations were measured using an atomic force microscope (Dimension 3000, Digital Instruments) in the tapping mode. The Raman spectrum from the wear pad was obtained (Renishaw, System 1000) and wear tests were initiated. In the present study, constant speed drag tests and sweep tests were conducted. In all constant speed drag tests, the head was positioned on a track near the outside radius of the disk, while in the sweep tests the head was positioned to sweep over 80% of the available disk area. The indentation dimensions were measured at periodic intervals. The plastic upset volume present at the periphery of the indentations was very small and the ridges forming this region were found to wear out very quickly. Hence, the effect of initial plastic deformation was neglected.

A spindle speed of 3600 rpm was used in all the tests. Under normal operating conditions, the head was loaded on the disk with a force of 350–400 μN. The linear velocity between the slider and the disk was approximately 7.4–7.8 m s^{-1} near the outside diameter. The sweep frequency was 0.533 Hz. The load on the heads was imposed by deflecting the suspension to the required amount after its stiffness had been determined. A microscope was employed for measuring the deflection of the tip of the suspension. The accuracy of the tip deflection method was approximately 10 μm, which gave a loading error of approximately 10–20 μN. The loading used in the tests was in the range of 300–1600 μN. The heads were characterized by AFM and Raman spectroscopy at intermediate stages during the wear tests.

4. Results

Table 1 contains a summary of the details of the experiments reported in this study. All experiments were conducted under ambient conditions at a spindle speed of 3600 rpm. For the sweep tests reported, the sweep frequency used was

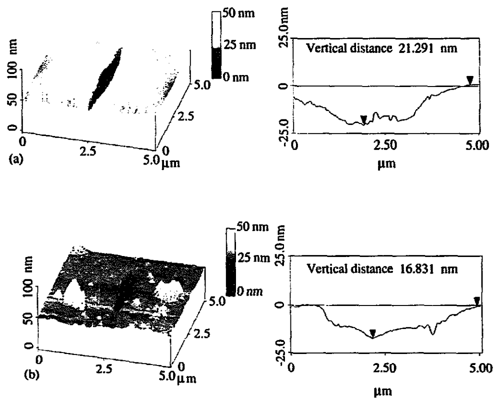

Fig. 6. AFM surface scans and sectional plots of a typical indentation, (a) prior to testing and (b) after one week of constant speed drag testing.

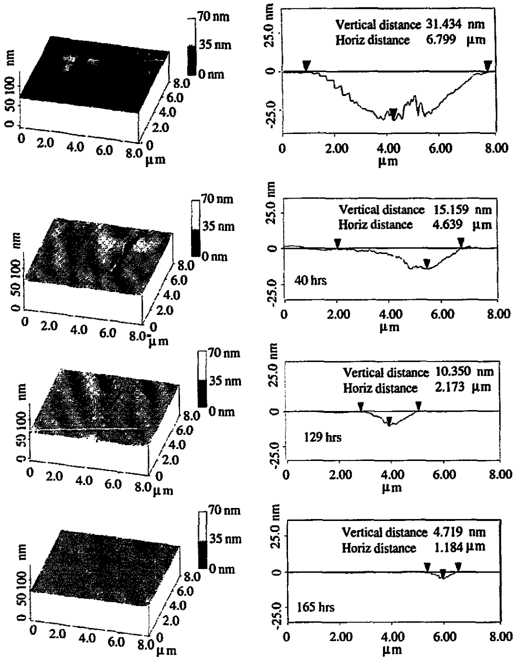

Fig. 7. AFM images and sectional plots of a typical indentation at various stages of a sweep test.

0.533 Hz. The sweep amplitude was 14 mm. Fig. 6 shows AFM surface scans and sectional plots for a typical indentation before and after a drag test under a load of 343 μN and a linear velocity of 7.84 m s^{-1}. The observed change in the depth of the indentation was approximately 4.5 nm after 162 h of continuous sliding over a fixed track. Fig. 7 shows another sequence of AFM images and sectional plots of a typical indentation from a sweep test. In this test, the indentation was monitored periodically at time intervals of about 40, 129 and 165 h, respectively. The load in the test was 620 μN, which was almost twice the load of the drag test in Fig. 6. The total wear depth obtained after 165 h was 26.7 nm. The wear volume per hour is plotted in Fig. 8(a) and Fig. 9(a) against load for the drag and sweep tests, respectively. We observe that the wear volume increases with increasing load. In Fig. 8(b) and Fig. 9(b), the wear volume is plotted as a function of sliding distance for both drag and sweep testing. Again, we observe that the wear volume increases with sliding distance. If a straight line were fitted through the data points, the line would not pass through the origin but would show a vertical offset at zero sliding distance, i.e. wear vs sliding distance is non-linear in the initial stages of sliding. Comparing Fig. 8(a) and Fig. 9(a), we note that the wear volume in a drag test is lower than in a sweep test for the same load and sliding distance.

5. Discussion

The experimental results obtained can be considered in terms of Archard's wear equation [11], which relates the wear volume W to the contact load L, the sliding distance s and the hardness H of the wearing surface by

$$W = KLs/H \qquad (1)$$

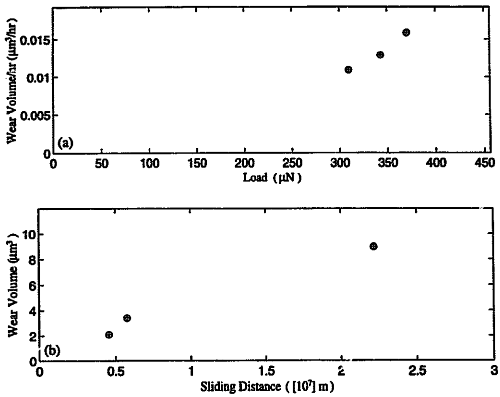

Fig. 8. Wear volume as a function of (a) load and (b) sliding distance in drag testing.

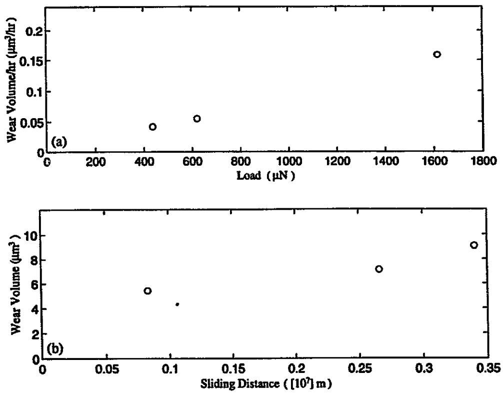

Fig. 9. Wear volume as a function of (a) load and (b) sliding distance in sweep testing.

Here, K is the so-called wear coefficient. In general, K is affected by interface topography, environmental factors such as temperature and humidity, mode of lubrication, contaminants, etc. According to Rabinowicz [6], typical wear coefficients for adhesive wear are in the range of 10^{-6}–10^{-8} for sliding of well lubricated dissimilar materials. Rabinowicz suggests that minimum wear can be obtained in the "burnishing regime" which is a type of adhesive wear.

For most wear situations K is high at the beginning of sliding and decreases to a low value when sliding is continued for a long time. In this study, the variation of K was investigated as a function of load and sliding distance for sweep and constant speed drag testing. From Fig. 10, we observe that the average value of the wear coefficient K is lower in a constant speed drag test than in a sweep test. A typical value of K in a drag test is about 0.2×10^{-10}, while a typical value of K in a sweep test is 0.6×10^{-10}, i.e. the value of K is approximately three times larger in a sweep test than in a drag test. This result is related to the fact that the head encounters a much larger unworn disk area in a sweep test than in a drag

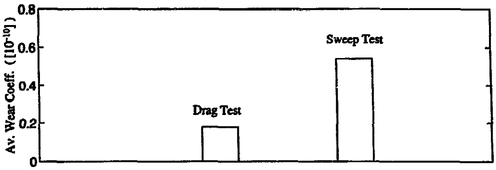

Fig. 10. Average wear coefficient.

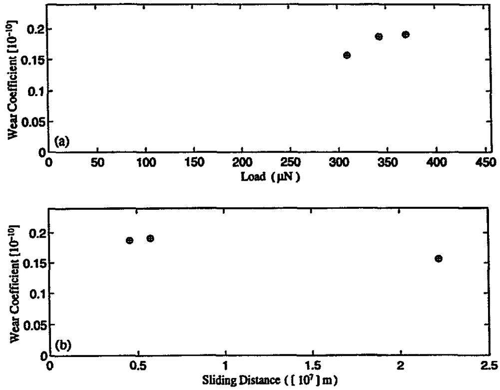

Fig. 11. Variation of wear coefficient with (a) load and (b) sliding distance in drag testing.

test, where the head remains on a single track. Since an unworn disk surface is more abrasive than a worn disk surface, wear in a sweep test is larger than in a constant speed drag test. Fig. 11 and Fig. 12 show the variation of the wear coefficients K as a function of load and sliding distance for both drag and sweep testing. Point A in Fig. 12 denotes a measurement taken in a sweep test during the initial stage of the test, while the data points denoted by B correspond to measurements after a long time test. We observe that K is nearly independent of sliding distance and load for large sliding distances (points B). However, at small distances in a sweep test (point A, Fig. 12), K is nearly twice the long distance result, i.e. K decreases from an initially high value at the beginning of sliding to a low, steady-state value.

The result that K is larger in the initial stages of a sweep test appears to be due to the burnishing of the asperities on the disk surface by the head with a subsequent reduction in the abrasiveness of the disk surface. It is interesting to note that this process seems to be completed after approximately 40 h of testing. A similar high initial value for K should also be observed in a drag test on a fixed track. However, since the asperities in a fixed track test are burnished very fast, the reduction in the abrasiveness of the surface occurs in too short a time for experimental observation.

The results obtained in this investigation indicate that Archard's equation, which has been used extensively for describing wear in macro-tribology, is also useful for describing nano-wear of extremely lightly loaded contacts, such as those encountered in contact recording wear situations. Furthermore, the small value of K indicates that the wear situation is of the burnishing type [6].

In addition to the wear measurements, we have conducted Raman spectroscopy (Renishaw, System 1000) to investigate and characterize changes in the carbon morphology before and after wear testing (Fig. 13). However, no changes in the morphology of the carbon after the wear tests were observed as indicated by a change in the position, shape or intensity ratio of the D and G bands. On the other hand, a large increase in fluorescence was observed after wear testing, Fig. 13(a). This increase in fluorescence is possibly related to the generation of atomic scale defects in the surface layers of the contact region and may be useful in characterizing the wear mechanisms taking place [12].

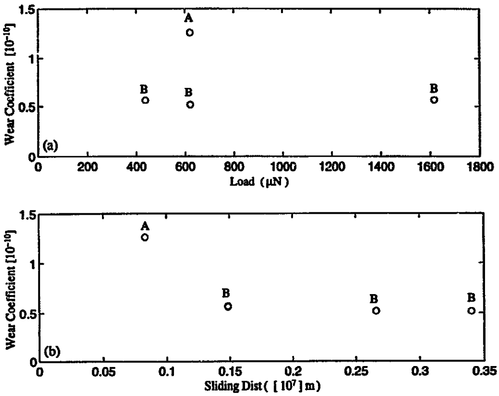

Fig. 12. Variation of wear coefficient with (a) load and (b) sliding distance in sweep testing.

It should be noted that the material characteristics of the sample determine the depth to which the laser radiation penetrates into the sample, which in turn determines the volume of material probed by the spectrometer. Tests on DLC films whose thickness was in the range of 200 nm–4 μm, deposited on silicon wafers using the same plasma enhanced chemical vapor deposition process show that the laser radiation can penetrate down to a depth of 1 μm into the carbon. This can be seen from the Raman signal in Fig. 13(b) obtained from a 1000 nm thick DLC film. The peak from the silicon substrate at 520 cm^{-1} can still be seen. Hence, it is important to realize that the Raman signal does not probe just the surface layers and the effects of wear on the surface may be masked by the signal from the material underneath.

In some of the tests, build-up of contaminants at the interface was observed. The head–disk test set-up was operating under normal laboratory temperature and humidity conditions. The set-up was completely enclosed by a cover which

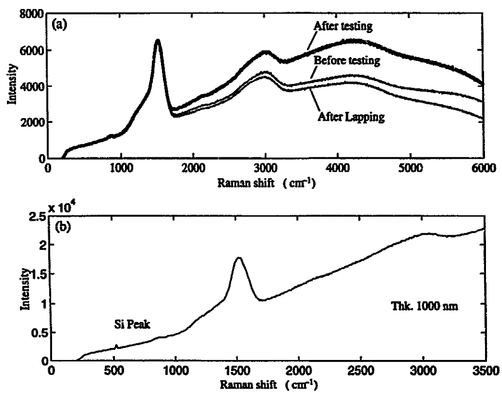

Fig. 13. (a) Raman spectra before and after lapping and after testing; (b) Raman spectrum from 1000 nm DLC film on Si wafer.

was air-tight. Contamination was observed as attached debris covering portions of the contact surface. The Raman spectrum of the contaminants did not indicate the presence of any new chemical species. It is possible that the signal from the contaminated areas is not Raman active. On the other hand, since the amount of debris is very small, it is also possible that the amount is too small to yield an appreciable signal.

In this study we have been concerned only with the measurement of slider wear. Although disk wear is present at the interface, it is difficult to measure since the ratio of the contact area of the disk surface to the contact area of the slider is very large, i.e. wear of the disk surface is distributed over a large region.

6. Summary

Nano-wear has been studied for the interface of a contact recording head and a magnetic disk by monitoring the change in size and depth of artificially introduced indentations in the wear surface of the slider for the measurement of wear. Wear rates of the order of 4.5 nm per week have been found for constant speed drag testing at a nominal load of 350 μN, while wear rates of the order of 9–12 nm per week have been observed during sweep testing. These wear rates are expected to decrease even more with continuing improvement in the material and lubricant combinations at the interface. Since the wear rate of a contact recording head is a function of a number of design and operating parameters, it is apparent that each new head design exhibits a different wear rate, i.e. it is not possible to make a general statement as to whether the wear rates observed will be acceptable for a general contact recording situation or not.

The average wear coefficients using Archard's wear equation were found to be of the order of 0.2×10^{-10} and 0.6×10^{-10} for drag and sweep testing, respectively. These values are lower by two orders of magnitude compared to the lowest values reported in the literature for macro-wear sliding situations [6]. The wear coefficients were found to remain nearly constant with load and sliding distance for long time experiments. However, during initial stages of wear a higher wear coefficient was observed. The indentation method for nano-wear measurement shows promise for the evaluation of wear in other nano-wear sliding situations and it is expected that the method will provide valuable data for the tribological performance of future contact recording applications. Practical applications include design life estimation for various contact recording and proximity recording applications in the magnetic storage industry as well as other micro-electro-mechanical systems. The technique should also be useful for other nano-wear situations.

Acknowledgements

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Biographies

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M.H. Azarian: is a senior tribology engineer at Censtor Corp. in San Jose, CA. He received his BSE in Chemical Engineering at Princeton University. He then joined Philips Research Laboratories in Eindhoven, Netherlands for two-and-a-half-years, studying interaction phenomena in magnetic particle suspensions. He went on to receive an ME and Ph.D. from the Department of Materials Science and Engineering at Carnegie Mellon University, where his thesis work focused on tribology of carbon overcoats for rigid disk recording media. Since joining Censtor in 1993, he has been working on characterization and development of the contact recording interface for high density magnetic recording. His primary research activities involve wear, surface topography, friction and long term reliability.

F.E. Talke: received a Diploma-Ing. degree from University of Stuttgart, Germany in 1965 and MSc and Ph.D. degrees from the University of California, Berkeley in 1966 and 1968, respectively. From 1969 to 1986, he was in the IBM Research and Development Laboratories in San Jose, CA, and in 1984 he spent one year as a guest professor at the University of California, Berkeley. He is the author of more than 120 publications and holds 11 US patents. His research interests are in the areas of the head–disk and head–tape interface mechanical design related to magnetic recording technology, tribology and high precision instrumentation. Dr Talke accepted a position as an Endowed Chair Professor at CMRR effective March 1986.