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TRIBOLOGY OF ADVANCED MAGNETIC TAPES AND HEADS FOR ULTRAHIGH-DENSITY MAGNETIC RECORDING

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

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****

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1998

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Physics Graduate Program
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Mechanisms of friction and wear between solid surfaces in physical contact and in relative motion have been investigated in this study. An experimental system and test methodology based on principles of magnetic recording was developed which allows an unprecedented ability to look inside of a sliding interface. Using a modified commercially available Hi-8 video cassette recorder as a magnetic tape transport, magnetometer and tribometer, sliding tests were conducted while measuring friction force, head-to-tape spacing to nanometer vertical resolution and intermittent signal dropouts due to loose wear debris particles passing through the contact interface to sub-μs duration. Evolution of friction and wear with repeated sliding, temperature and humidity effects on the sliding interface and origins of friction and wear at an asperity level were investigated with the experimental system. Magnetic tape samples with various constructions with different composition, surface texture and lubricant thickness, were used in the experiments. Methodologies to measure magnetic head and tape wear were developed and applied to worn specimens. Development and use of the novel magnetic recording experimental strategy and apparatus has allowed new understanding of friction and wear mechanisms on the nanometer level for a macroscopic sliding interface. The experimental results combined with newly developed analytical models has allowed the definition and discovery of low friction and near zero wear sliding surfaces.

Three body abrasion by loose wear debris particles was found to be the primary mechanism governing friction and wear in sliding experiments. Generally, wear starts out from the abrasive action of loose wear debris particles leading to a smoother tape surface which then results in mild adhesive wear. Metal evaporated (ME) magnetic tapes were found to be less durable than particulate metal particle tape. Capillary condensation of meniscus water films between sliding surfaces governed temperature and humidity effects, and introduced meniscus forces which influenced friction force and lubrication mechanisms. An analytical model based on the Kelvin equation was developed to predict
the effect of capillary condensed water vapor on the tribological behavior of the sliding interface. The model is in agreement with the experimental results.

In the study of the origins of friction and wear at an asperity level of tapes with a thin metallic magnetic layer, it was found that enough asperities should be present to prevent plastic deformation of high asperities. High friction force was measured with tapes that exhibit plastic deformation, and growth of real area of contact due to shear stress brought on by friction force is the most plausible explanation. Smooth surfaces with high isolated asperities should be avoided to prevent brittle fracture of asperities which results in generation of loose wear debris particles and high friction force. A wear resistant surface was discovered that exhibited elastic deformation of asperities and low friction force. The wear resistant surface has enough asperities to prevent plastic deformation and brittle fracture. An analytical model based on the principles of plastic deformation and brittle fracture was developed and combined with experimental data to determine the subtle origins of friction and wear.

In the study of pole tip recession (PTR) in advanced thin-film tape inductive write heads for tape recording applications, the usage of alternate pole tip materials with superior magnetic and magnetic properties, such as iron aluminum nitride, or application of hard carbon coatings over the head structure, were both able to prevent growth in PTR with sliding distance against metal particle tape. Mechanism of differential wear is intimately related to varying mechanical properties of different materials in the composite head structure, and differential wear is mitigated or eliminated with mechanically harder pole tip materials or application of a coating to the head structure.
Dedicated to my mom and dad
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CHAPTER 1

INTRODUCTION

From turning the pages of this dissertation to walking across the room, friction and wear phenomena abound in everyday life. Despite their being familiar, these processes are complex and often not well understood. Magnetic recording devices, and in particular, magnetic tape recorders, are systems that allow us to look inside of a sliding interface, and consequently, allow us to further understand complex friction and wear phenomena.

The study of friction and wear mechanisms in a sliding interface is interesting from a technological point of view, for instance, in developing a low friction and wear resistant magnetic tape. Origins of friction and wear in sliding interfaces also has fundamental scientific importance and has intrigued scientists for hundreds of years. Implementation of methods for friction and wear reduction into machines and devices can save valuable energy and natural resources. According to some estimates, losses in the U.S. resulting from ignorance of tribology amount to about 6% of the gross national product or about $200 billion per year, and about a third of the worlds energy resources is lost to friction.

The objectives of this dissertation are to develop experimental apparatus, associated instrumentation and experimental methodology to determine friction and wear mechanisms, durability, origins of friction and wear, environmental effects (temperature and humidity) and mechanisms of differential wear in magnetic head-to-tape sliding interfaces. Various friction and wear phenomena studied in this dissertation are expected to have relevance to other sliding systems. Nanometer vertical and sub-μs temporal resolutions of the measurement system allow us to look inside macroscopic sliding interfaces with unprecedented resolving power.
The following sections of this chapter contain background information on friction, wear and magnetic recording with an emphasis on fundamental aspects relevant to phenomena addressed in later chapters. Chapter 2 provides details of various experimental apparatus, head and tape specimens and methods and procedures. Chapters 3-5 give results of the three major investigations in this dissertation. Each of Chapters 3-5 begins with specific background material relevant to the topic at hand, and summary sections are given to wrap up various topics. Chapter 3 gives results of investigations of friction, wear and durability of metal evaporated (ME) and metal particle (MP) magnetic tapes in a rotary head tape drive. Chapter 4 gives results of investigations of environmental effects (temperature and humidity) on friction and wear mechanisms of ME and MP tapes in a rotary head tape drive. In Chapter 5, results of investigations of pole tip recession or PTR (relative wear of a pole tip with respect to the air bearing surface or ABS) in thin-film inductive write heads in a linear tape drive are given.

1.1 Friction

Friction is defined to be the resistance to motion that occurs when two contacting solids slide tangentially with respect to each other, or when an attempt to cause motion is made by applying a force with a tangential component (Bowden and Tabor, 1950; Rabinowicz, 1965; Bhushan, 1996). Friction force is the force exerted on one body by the other and is directed opposite to the relative tangential displacement. There are two regimes of friction, static and kinetic, that will be addressed now. Static friction is the friction that occurs when an applied force is insufficient to cause motion, whereas, kinetic friction is applicable when relative motion occurs. Measurements of friction force in this dissertation are of kinetic friction force.

There are two basic laws of friction, often referred to as Amontons laws, that are generally well obeyed to within a few percent (Bowden and Tabor, 1950; Rabinowicz, 1965; Bhushan, 1996). Amontons first law states that the friction force is independent of the apparent area of contact, and his second law states that the friction force \( F \) is proportional to the normal load \( W \). Amontons second law can be written as

\[ F = \mu W \]  

where \( \mu \) is the coefficient of friction. Although these laws are credited to the French engineer Amontons as he stated them in 1699, Leonardo da Vinci (1452-1519) had stated them in words and verified them experimentally (Bowden and Tabor, 1950).
Origins of friction force, which determine its magnitude, are and have always been of utmost importance. Methods of reducing friction, such as using liquid lubricants, dates back to about 1900 B.C. (Bowden and Tabor, 1950). With the beginning of the modern era in friction research or Amontons work, came curiosity and speculation as to the origins or causes of friction. Amontons and other researchers of friction from France believed that the origin of friction was surface roughness, whereas, in England, the prevailing theory was that cohesion between the bodies was the cause of friction. Cohesion was first suggested to be a cause of friction by Desaguliers.

The current understanding of friction is that interfacial adhesion and the energy consumed in deforming the surfaces are primarily responsible for friction force (Bowden and Tabor, 1950; Rabinowicz, 1965; Bhushan, 1996). It can be written that

$$ F = F_A + F_D $$

(1.2)

where $F$ is the total friction force, $F_A$ is the adhesion component to friction force and $F_D$ is the deformation component to friction force. The adhesion component to friction can be written as

$$ F_A = A_r s $$

(1.3)

where $A_r$ is the real area of contact and $s$ is the shear strength of adhesive junctions. $A_r$ is the actual area of intimate contact between rough contacting surfaces. For plastically deformed asperities, $A_r$ depends only on the normal load and hardness ($H$) of the softer material, whereas, for elastically deformed asperities, $A_r$ depends on normal load, composite elastic modulus ($E'$) and surface topography (Bhushan, 1996). The shear strength $s$ is determined by physical and chemical interactions on a molecular scale. The deformation component of friction is often referred to as the plowing component of friction particularly in the case of hard sharp asperities sliding over a soft surface. A simple model of a circular cone of roughness angle $\theta$ (larger $\theta$ makes the cone sharper) pressed into a softer surface under load $W$ and sliding with respect to the softer surface is given by Rabinowicz (Rabinowicz, 1965). He found that

$$ F_D = \frac{(W \tan \theta)}{\pi} $$

(1.4)

This simple model is not sufficient to model deformation during sliding, and more sophisticated models exist, but the simple model is sufficient to show that sharper asperities increase the deformation component of friction.
1.2 Wear

Wear is the removal of material from solid surfaces due to mechanical contact or action (Rabinowicz, 1965; Bhushan, 1996). There are several forms of wear that are known to occur, and among them, only adhesive and abrasive wear mechanisms will be described here because these are the wear mechanisms relevant to this dissertation.

Adhesive wear involves pulling fragments off of one surface which adhere to the other surface and occurs due to the formation of junctions at real contact areas. It may be that the junction is stronger than the surrounding bulk material and that the break during sliding occurs within one of the materials which generates a loose wear debris particle. Abrasive wear involves a rough hard surface sliding over a soft surface (2 body), or a loose wear debris particle caught between two sliding surfaces (3 body). In either case, a series of grooves is ploughed (plastically deformed) in either one or both of the surfaces. Adhesive wear is more common and generally cannot be prevented, but generally is milder than abrasive wear. Abrasive wear often gives high wear rates and early failure of sliding interfaces.

With this dissertation and other studies of ultrasmooth surfaces sliding under ultra-light loads, new more refined definitions of wear need to be introduced into the literature. Based on section 3.3 of this dissertation, a new definition of wear may be that wear is the change in surface morphology due to mechanical contact or action. Surface changes may be very subtle and only measurable with sensitive instruments like an atomic force microscope (AFM) and may or may not involve the removal of material from the surface. At an asperity level, it may be sufficient to define plastic deformation and brittle fracture as the relevant wear mechanisms for these ultrahigh performance interfaces. In any case, terminology will evolve as more fundamental understanding of friction and wear mechanisms emerge in developing high performance designer interfaces.

1.3 Magnetic Recording

Magnetic recording was first used to record information by Valdeman Poulsen in 1898 with his telegraphone which recorded and reproduced sound. In 1927, J. A. O'Neill patented a paper tape with magnetic coating for audio recording. In 1951, video recording was first accomplished with magnetic tape. Need for data storage brought on the first magnetic disk drive in 1955 by IBM. Tape and disk drives are, even today, widely used
for audio, video and data storage applications. Materials engineering, magnetics, system
and device development and tribology are all areas that continue to be developed and
have enabled ever increasing recording densities in magnetic recording devices.

Magnetic recording and retrieval is accomplished by relative motion between a
head transducer and magnetic medium which are in close proximity. For inductive heads,
which are used in experiments discussed in this dissertation, recording is accomplished
by varying the current in wires wound around the head core. Winding current produces
magnetic flux in the core and produces a fringing magnetic field at the head gap which
magnetizes the medium. For retrieval or reproduction of the recorded information,
demagnetization fields from the medium are collected by the core and voltage is induced
across the windings by electromagnetic induction. The magnetic recording process is
complex and magnetic requirements of the heads and media are generally different and
demanding. The intention here is not to develop magnetic recording theory, and readers
can find necessary details in the literature (Mee, 1964; Mee and Daniel, 1996).

The importance of friction and wear in magnetic recording arises from the fact
that physical spacing between the head and medium should be as small as possible to
prevent spacing loss. R. L. Wallace Jr. was the first to experimentally verify and also
develop a theoretical basis for spacing loss during the reproduce process (Wallace, 1951).
The spacing loss during playback, or the Wallace equation, can be written as
\[ \Delta dB = -54.6 \frac{\Delta d}{\lambda}. \] (1.5)
where \( \Delta dB \) is the incremental change in head output level, \( \Delta d \) is the incremental change
in head-to-medium spacing and \( \lambda \) is the recording wavelength. Spacing loss is
proportional to \( \Delta d \) and inversely proportional to \( \lambda \). Origin of spacing loss is the
exponential decay of the magnetic scalar potential in the direction normal to a sinusoidal
recording for a two dimensional geometry. Trends in magnetic recording are to increase
the areal recording density which is accomplished by increasing both the track density
and linear density (decreasing \( \lambda \)). Spacing loss is magnified as linear recording density
increases which can be compensated by maintaining intimate contact (small spacing)
between the head and medium. This is usually accomplished by making heads and media
as smooth as possible.

The novel experimental strategy used in this dissertation is to measure the
reproduce head output decibel level for a sinusoidal magnetization pattern and correlate
this to changes in head-to-tape spacing during use via the Wallace equation. Nanometer
vertical (or normal) resolution of the experimental system allows an unprecedented
unique way of looking inside of a sliding interface.
1.4 Overview

This dissertation includes material associated with two experimental apparatus and their associated instrumentation, a rotary head tape drive and a linear tape drive. The rotary head tape drive has instrumentation to write signal onto the tape and to read signal from the tape, whereas, the linear tape drive does not have read/write capability and just serves as a vehicle to pass tape over a head.

1.4.1 Rotary Head Tape Drive

In the rotary head tape drive, magnetic heads are mounted on a high velocity rotating drum, and the magnetic tape is wrapped around the drum and guided at low velocity past the drum (Bhushan, 1992; Bhushan, 1996; Mee and Daniel, 1996). A hydrodynamic air film is established between the tape and drum causing the tape to float above the drum. However, the magnetic heads protrude from the drum and directly contact the magnetic tape surface under a normal loading force. Physical contact between the rotary heads and tape under normal load at high relative velocity brings friction and wear phenomena into play. In real world applications, both the heads and tapes are used repeatedly, and durability is a practical issue to be concerned with. Tribological (tribology is the study of friction, wear and lubrication of contacting solid bodies in relative motion) and magnetic performance should be stable over the life time of the components for optimum performance. Various tapes are commercially available which are constructed differently, and their durability and performance are expected to differ. Determination of tribological mechanisms for the tapes and their relation to durability and performance can lead to improvements and further development of recording technology.

In the rotary head tape drive, changes in the physical separation between the head and tape surfaces can be measured with a resolution of about 1 nm by using basic principals of magnetic recording. Recognition of the powerfullness of this technique and its implementation into the experimental system has enabled the development of unprecedented understanding of the interplay of friction, wear, lubrication and surface topography in a sliding contact interface.
1.4.2 Linear Tape Drive

In the linear tape drive, the magnetic head is stationary, and the magnetic tape is guided over the head at high velocity (Bhushan, 1992; Bhushan, 1996; Mee and Daniel, 1996). A hydrodynamic air film is established between the tape and head causing the tape to float above the head. However, air bleed slots on the head cause the tape to directly contact the head at the write and read elements under a normal loading force. Physical contact between the head and tape under normal load at high relative velocity brings friction and wear phenomena into play.

Advanced thin-film tape heads for ultrahigh-density recording applications require low and constant PTR to minimize spacing loss of signal. The emphasis here is to determine the effectiveness of mechanically superior alternate pole tip materials and the application of hard carbon coatings on the head in preventing growth of PTR. Development of measurement techniques to determine differential wear of the heads and characterizing growth of PTR as the heads were slid against magnetic tapes was performed to further develop advanced thin-film tape heads.
CHAPTER 2
EXPERIMENTAL

2.1 Apparatus

2.1.1 Rotary Head Tape Drive

A commercial Hi-8 VCR (Sony EVC-100) with 4 heads was used as a tape transport, magnetometer and tribometer. In this transport, linear tape speed is 14.3 mm/s, and the speed of the rotary heads is 3.8 m/s with inlet and outlet tensions of about 0.10 N and 0.15 N, respectively. The given tape tension, a head width of 60 μm, a measured head longitudinal radius of curvature of 7.8 mm and a wrap angle of about 0.1 rad (contact length of about 0.8 mm) produced a normal load of about 15 mN and an average contact pressure at the contact region of the head and tape of about 300 kPa. The VCR was instrumented to measure friction force between the rotary heads and tape, rms head output and signal dropouts to sub-μs duration (Patton and Bhushan, 1996a; Patton and Bhushan, 1997; Patton and Bhushan, 1998a).

The experimental apparatus is shown schematically in Fig. 2.1 (a). It consists of a Hi-8 VCR, buffers/amplifiers, rms signal converters, a dropout counter, an A to D converter and computer. The VCR consists of a loading/unloading mechanism, a rotary upper drum, a stationary lower drum, electronics and a tape transport. The tape transport consists of various guide pins, a roller guide, a pinch roller, a capstan and a tension regulator. Magnetic tape is unwound (driven by the capstan and reel motors) from the supply reel and guided past the rotating heads (which are mounted on the rotary drum) before being wound onto the take up reel. An air film is established between the rotary upper drum and tape which causes the tape to float above the rotating drum. However, the heads protrude 60 μm from the drum, which brings them into contact with the tape.
Figure 2.1. Schematics of (a) commercial Hi-8 VCR used as a tape transport, magnetometer and tribometer and associated instrumentation and (b) MIG read/write video head.
Friction force was measured by monitoring the voltage across the motor used for drum rotation, and friction force was obtained using a previously developed calibration procedure (Patton and Bhushan, 1996b). In the calibration procedure, a known tangential force was applied to the drum outer surface (with the drum spinning and no tape loaded in the drive), and the motor voltage was measured for various values of the applied force. A commercial force gage designed to measure the tangential force was used for the calibration. A tangential force was applied to the drum surface by orienting the deflection beam of the force gage normally to the outer surface of the rotary upper drum. One end of the deflection beam was brought into contact with the rotating drum (which resulted in a tangential force on the drum), and the other end, connected to a spring system, deflected a pointer. The tangential force was obtained directly from the pointer deflection. The motor voltage as a function of applied tangential force curve was found to be linear with slope 54 mV/mN. The resolution of the friction force measurement was 100 μN. Friction force of about 7 mN was measured in streaming mode and corresponds to a coefficient of friction of about 0.4.

Head output was measured in an rms voltage format using an rms signal converter (Analog Devices model AD637JQ). Playback signal from the video heads and friction signal from the motor used for drum rotation were processed through buffer/amplification stages (Analog Devices model AD811AN), and the rms voltage of each signal was measured using wide bandwidth (about 10 MHz) rms signal converters. Time constant of the rms signal converter was chosen to be about 33 ms, which corresponds to about 10 read envelopes. Head output data are presented in a voltage decibel format, and the reference 0 dB voltage is usually the initial playback rms voltage for a given tape. Thus, 0 dB for a given tape should usually be interpreted as an arbitrary voltage level. In cases where relative output between tapes was of interest, 0 dB was taken to be the system noise level of 5 mV. During the seven minute streaming and pause mode experiments, motor voltage and rms head output were sampled at 1 kHz using an A to D converter. Data were averaged to give an effective sampling rate of 4 Hz, and data were stored in a personal computer. Snapmaster data acquisition software was used to control the A to D board (Omega DAS 16G, 12 bit board with 5 mV resolution) with the computer.

Signal dropouts were measured using a 40 MHz bandwidth single channel dropout counter (System 20 VTT multi-level dropout tester by Doradus Corp., Minneapolis, MN). Signal dropouts occur due to sensitivity of head output to head-to-tape spacing. Figure 2.2 (a) shows the top view of the rotary upper drum in Figure 2.1 (a). As the tape translates past the rotary drum, the tape floats on an air film established
Figure 2.2. Schematic illustrations of: (a) top view of rotary upper drum region of VCR, (b) magnified view of head-to-tape contact region under normal operating condition, (c) magnified view of head-to-tape contact region with a wear debris particle in the interface and (d) variation of head output level for an a-b dB and c-d µs dropout caused by a wear debris particle.
between the tape and drum, and the tape directly contacts the magnetic heads due to each
heads' protrusion from the rotary drum. \( T_1 \) and \( T_o \) are the inlet and outlet tensions,
respectively. Figure 2.2 (b) shows a magnified view of the head-to-tape interface for the
case of no wear debris particle between the head and tape illustrating that the tape directly
contacts the heads. The drum and tape velocities are \( v_d \) and \( v_t \), respectively.

Figure 2.2 (c) illustrates how a wear debris particle can increase the spacing
between the head and tape when it is in the interface. The increase in spacing will cause
the signal level to drop according to the Wallace equation as shown by the curve in Fig.
2.2 (d). An a-b dB and c-d \( \mu s \) dropout is defined to occur when head output falls below a
threshold signal level a, but not below signal level b, for a duration of time \( \Delta t = t_2 - t_1 \n greater than c \( \mu s \) and less than d \( \mu s \). Twenty classes of dropouts defined by ranges of
dropout depth and duration can be measured simultaneously by the tester. Dropout depth
and duration are selectable in the ranges of 1 to 22 dB in 0.5 dB increments and 0.5 to
300 \( \mu s \) in 0.5 \( \mu s \) increments, respectively. In these experiments, the various ranges of
dropout depths and duration selected are: 4-6, 6-9, 9-12 and >12 dB; 0.5-3, 3-10, 10-20,
20-50 and >50 \( \mu s \).

2.1.2 Linear Tape Drive

A linear tape drive (Honeywell 96) was used as a tape transport. Figure 2.3 shows
a schematic of the experimental apparatus. A 0.6 km length of tape was shuttled back and
forth across the head in a shoeshine mode until either 500 or 1000 km (depending on the
particular experiment) of tape had slid against the stationary head specimen. Head
specimens were secured in a head mount, and using the x stage, were brought into contact
with the tape. Magnetic tape is unwound from one reel and guided past the stationary
head before being wound onto the other reel. An air film may or may not be present
between the tape and head depending on the tape speed, tape tension and head position.
Tape tension is applied by a vacuum column. The amount of tape in the vacuum column
is monitored with photosensors and an LED source, and the signal controls the reel
motors through a feedback loop. Vacuum pressure controls tape tension and can be
adjusted by varying the voltage to the DC vacuum motor. The linear tape speed in the
drive is variable, but all experiments in this dissertation were conducted at 3 m/s sliding
velocity. Tape tension was either 1.0 N (section 5.2 or alternate pole tip materials) or 1.7
N (section 5.3 or hard carbon coatings) in the experiments. The drive was instrumented to
measure friction force between the head and tape samples. Strain gages arranged in a full
Wheatstone bridge were mounted on a thin web in series with the head specimen (Bhushan and Lowry, 1995). Friction data were recorded with a chart recorder.

### 2.1.3 Other Tools

In addition to the rotary and linear tape drives and their associated instrumentation, other devices were used, particularly to characterize the surface topography of virgin and worn head and tape samples. The two instruments used to characterize surface topography of head and tape samples are the AFM and non-contact optical profiler (NOP). Description of both of the devices follows that given in Bhushan’s book (Bhushan, 1996).

Two AFMs were used for surface characterization in this dissertation. Both are products of Digital Instruments Inc. For head topography measurements, stand alone AFM (SAAFM) was used, whereas, for tape topography measurements, Dimension 3000 AFM was used. SAAFM is somewhat portable and allows samples of up to several inches in height to be measured. Dimension 3000 AFM is not portable and generally performs better than SAAFM at smaller scan size (on the order of $1 \times 1 \mu m$ scan size). AFMs used in this dissertation scan a tip over a stationary sample. The tip is mounted on a piezoelectric (PZT) transducer tube scanner which has electrodes. Applying a voltage to the electrodes allows scanning of the tip in the horizontal x-y plane in a raster pattern and movement of the tip in the vertical z direction.

A sharp tip mounted on the end of a flexible cantilever is brought into contact with a sample. Both normal and friction forces acting on the tip are measured using a laser beam deflection technique (Bhushan, 1996). A laser beam from a laser diode goes through a prism which directs it onto the back of the cantilever (which is tilted down at about $10^\circ$ from the horizontal) near the tip. The reflected beam from the cantilever reflects off a mirror onto a quad photodetector (split photodetector with four quadrants). The differential signal between the top and bottom photodiodes is the AFM signal which is a measure of the cantilever vertical deflection. The surface topography of the sample causes vertical deflection of the tip as the tip scans across the surface. The tip deflection changes the position of the reflected laser beam as it enters the photodetector which changes the differential signal between the top and bottom photodiodes. Topographic imaging was done in height mode in which the normal force is held constant by adjusting the tip height (with the PZT) according with the surface topography. The PZT height variation is the measure of the surface roughness of the sample.
Figure 2.3 Schematic diagram of the linear tape drive and test configuration (from Bhushan and Lowry, 1995).
An NOP (WYKO model TOPO 3D) was used in this dissertation for surface characterization of magnetic tapes. NOP operates on the principle of optical interference. A Mirau interferometer is used with a single 40x objective lens (Bhushan, 1996). The light source is a tungsten halogen microscope illuminator with a spectral filter that passes a central wavelength of 650 nm with a pass band of 40 nm. The reference surface in the interferometer is mounted on a PZT so that it can be moved to measure the phase of the interference pattern. The interference fringe pattern can be viewed through an eyepiece. A 256 x 256 pixel charge-injection-device (CID) image sensor is illuminated by the fringes. Four interference images are digitized, each integrated over different 90° phase shifts of the fringes (Bhushan, 1996). A microcomputer calculates the phase at each detector element, and the surface height at each location is then known. Surface height data can be displayed in various formats and further analyzed by the software. Optical resolution is 0.8 μm and the spatial sampling interval is 1 μm for NOP measurements in this dissertation.

2.2 Magnetic Head and Tape Specimens

2.2.1 Rotary Tape Drive

Two read/write metal in gap (MIG) heads placed diametrically opposite on the drum have a core material of single crystal Mn-Zn ferrite with crystalline Sendust metal alloy (Fe-Si-Al) in the gap (Fig. 2.1b). MIG heads are needed to increase magnetic field strength to write onto high coercivity tapes used in the Hi-8 system. Two Mn-Zn ferrite heads without metal in the gap are also present on the rotary drum, one is used for automatic track finding and the other as a flying erase head.

Commercially available Hi-8 ME and MP tapes were used in the experiments. All of the tapes are 8 mm wide which is a specification for the rotary head tape drive. Figure 2.4 presents cross sections illustrating the basic structure of ME tape, ME tape substrate and MP tape. The major difference between ME and MP tapes is that the magnetic layer for ME tape is a thin continuous layer, whereas, for MP tape, the magnetic layer has magnetic particles uniformly distributed in a polymeric binder. ME tapes used in these experiments have a single layer magnetic coating of Co80Ni20. Figure 2.4 presents a cross section illustrating the basic structure of most commercially available ME tape. For all ME tapes used in this study, a 10 μm thick polyethylene terephthalate (PET) base film is used in the tape construction. A precoat of polymer film with particulate additives is
generally applied to the ME side of the PET substrate as shown in Fig. 2.4 (b). The precoat is about 10-25 nm thick. The precoat film on the ME treated side (magnetic layer side) generally contains inorganic particles (typically SiO₂). Generally, precoated PET that is used for ME tapes is smoother than PET that is used for particulate tapes. The polymer precoat is applied to reduce the roughness in a controlled manner from that of the PET surface and to provide good adhesion with the ME film. Particles are added to the precoat on the ME side to control the real area of contact and consequently the friction force between the finished tape and head surfaces. Particle size and areal density should be optimized to compromise between head output and friction force.

A continuous magnetic coating is deposited on the polymer film. The polymer film is wrapped on a chill roll during deposition which keeps the film at a temperature of 0 to -20 °C. Co₈₀Ni₂₀ material is deposited on the film by a reactive evaporation process in the presence of oxygen. Oxygen increases the hardness and corrosion resistance of the ME film. The deposited film, with a mean composition of (Co₈₀Ni₂₀)₈₀O₂₀, consists of very small Co and Co-Ni crystallites which are intermixed with primarily oxides of Co and Ni (Feurstein and Mayr, 1984).

A topical liquid lubricant (typically perfluoropolyether with reactive polar ends) is then applied to the magnetic coating (or to the diamondlike carbon or DLC coating if present) by rolling. The topical lubricant enhances the durability of the magnetic coating, and also inhibits the highly reactive metal coating from reacting with ambient air and water vapor. A back coating is also applied to balance stresses in the tape and for anti-static protection. Conventional back coats which are used for particulate tapes are inadequate for ME tape. The principal problem with conventional back coats is that they allow transfer of polymeric binder and pigment to the magnetic layer which results in excessive dropouts and head clogs (Chiba et al., 1989). Improved backcoats are used for ME tape.

In the case of MP tape, a PET base film is top coated with a polymeric binder with magnetic particles that are distributed uniformly in this layer to form the magnetic coating. Al₂O₃ head cleaning agents are also distributed uniformly in this layer to provide abrasivity to the tape. Smooth PET substrates (with typical rms roughness of 2-5 nm and peak-to-valley or P-V distance of 50-100 nm) are used. Particulates (such as silica or titania) with a bimodal distribution of sizes (with diameters of less than about 0.5 μm, and 2-3 μm) are added in the substrate as anti-slip agents (Bhushan, 1992). A back coating is generally applied to maintain the roughness of the front coat in the wound reel (which is required for low friction), and to improve tracking and to provide anti-static
Figure 2.4. Cross-sectional schematics of ME magnetic tape with typical thickness of various films, coated PET substrate for ME tape and MP magnetic tape.
protection. The back coat is optional, and if applied, consists of a polymeric coating containing inorganic particles (generally carbon black and TiO₂). Thicknesses of the PET base film, magnetic coating, back coating and the entire tape for MP tape used in this dissertation are 8.7, 1.5, 0.6 and 10.8 μm, respectively.

Thicknesses of the substrate, magnetic coating/back coating and DLC coating (if applied) for ME tapes used in durability studies in section 3.2 and environmental studies in Chapter 4 of this dissertation are 9.8 μm, 0.2 μm/0.8 μm and 10 nm, respectively. Three different kinds of ME tapes were used in durability studies in section 3.2 of this dissertation. Two kinds of ME tapes do not have a DLC coating and both have about 10 nm of liquid lubricant directly on top of the magnetic layer, but they differ in that one has surface waviness and the other is relatively flat. The third kind of ME tape has a 10 nm thick DLC coating on top of the magnetic layer with a liquid lubricant thickness of about 1 nm (on top of DLC coating) and is relatively flat. Surface topography of the virgin tapes was measured using a NOP. Table 2.1 gives roughness parameters for ME and MP virgin tape samples as measured by a NOP. The scan size for NOP measurements was 250 x 250 μm with a lateral resolution of about 1 μm. Nearly all roughness parameters are higher for wavy ME tape without a DLC coating as compared to flat tapes, which have similar roughness statistics. Surface slope, surface curvature, summit slope and number of summits per square millimeter (summit density) are larger for MP tape as compared to all of the ME tapes. Two relatively flat ME tape samples with and without a DLC coating, both without liquid lubricant (not commercially available), were specially prepared for cycling experiments. However, friction force was 40% higher, head output was 5-10 dB lower and dropout frequencies were more than order of magnitude larger than the worse performing commercial tapes. Data for these tapes will not be included in this dissertation.

Figure 2.5 shows 3-D profiles and 2-D line scans from a NOP of virgin ME with and without a DLC coating and MP tape surfaces. Waviness (of about 60 nm P-V and about 250 μm wavelength) of one kind of non-DLC ME tape is visible in the NOP profile and line scan, and bumps on the surface may induce localized wear and inhibit good recording performance at high linear recording densities due to spacing loss. Flat ME tapes with and without a DLC coating have similar morphology which appears to be superior for ultra high density recording as compared to wavy non-DLC ME tape. Surface asperities are seen on the MP tape surface which are not present on the ME tape surface. The 1 μm lateral resolution of the NOP does not allow it to resolve nanoasperities present on the ME tape surface (Patton and Bhushan, 1996b). The MP tape recording surface is
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<th>Flat ME no DLC</th>
<th>Flat ME with DLC</th>
<th>MP</th>
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<td>2.5/3.5</td>
<td>1.8/*</td>
<td>1.9/2.2</td>
<td>1.9/2.1</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.1/1.2</td>
<td>0.51/*</td>
<td>0.62/0.74</td>
<td>0.58/0.97</td>
</tr>
<tr>
<td>Summit-to-valley distance, nm</td>
<td>70</td>
<td>49</td>
<td>46</td>
<td>70</td>
</tr>
<tr>
<td>Summit-to-mean distance, nm</td>
<td>31</td>
<td>24</td>
<td>18</td>
<td>32</td>
</tr>
<tr>
<td>Number of summits per square</td>
<td>305/53</td>
<td>124/16</td>
<td>78/31</td>
<td>1200/240</td>
</tr>
<tr>
<td>millimeter(^b)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Profile zero crossings x, 1/mm</td>
<td>36</td>
<td>28</td>
<td>24</td>
<td>48</td>
</tr>
<tr>
<td>Profile zero crossings y, 1/mm</td>
<td>15</td>
<td>22</td>
<td>21</td>
<td>40</td>
</tr>
<tr>
<td>Average autocorrelation distance (µm)</td>
<td>33</td>
<td>32</td>
<td>30</td>
<td>27</td>
</tr>
</tbody>
</table>

\(^a\)Scan size for NOP is 250 × 250 µm

\(^b\)Mean and Rms values are given for all summits (first numbers) and summits with top 25% summit height (second numbers), and a threshold of 1.0 nm was used in defining summits on the surfaces

* Not enough summits in the top 25% of summit heights for partial statistics to be calculated

Table 2.1. Roughness data for virgin ME tapes with and without a DLC coating and MP tape used in play/rewind cycling experiments as measured with a NOP\(^a\).
Figure 2.5. 3-D profiles and 2-D line scans from a non-contact optical profiler (NOP) of three different ME, and MP tape surfaces.
relatively flat (as compared to wavy non-DLC ME tape), which should give excellent ultrahigh-density recording performance as compared to wavy non-DLC ME tape.

By measuring the head output level for each tape during the first play/rewind cycle, relative head outputs for the three tapes were obtained. Using head output for wavy ME tape without a DLC coating as the 0 dB level, head output for flat ME tapes with and without a DLC coating are -1.0 and -1.7 dB, respectively. Considering spacing loss incurred during both the record pass and first play/rewind cycle, a 1 dB change in head output corresponds to about a 6 nm change in head-to-tape spacing. This is true because for contact recording the Wallace factor changes from 54.6 to about 100 when spacing loss in both the record and playback processes are considered (Bertram and Niedermeyer, 1982; Ura et al., 1993). Thus, eliminating waviness of non-DLC ME tapes allows an effective reduction in head-to-tape spacing of about 10 nm. Addition of a 10 nm thick DLC coating to flat ME tapes increases head-to-tape spacing by about 16 nm.

For wavy non-DLC ME tape, it was suggested that buckling of the magnetic layer away from the substrate may be the cause of bumps on the ME tape surface (Patton and Bhushan, 1996b). However, further investigation into this phenomenon suggests that thermal damage to the substrate during deposition of the magnetic coating causes waviness of the ME tape surface. Figure 2.6 shows 3-D profiles from a NOP of the ME substrate front side, ME tape magnetic coating side and ME tape front side with magnetic coating removed by dipping the tape in a 10% (vol.) HCl solution for one minute. ME substrate front side has no bumps or waviness prior to deposition of the magnetic coating, and as discussed previously in reference to Fig. 2.5, bumps are present on the magnetic coating side of ME tape. By removing the magnetic coating with the HCl solution, the post deposition condition of the substrate was exposed for NOP analysis. ME tape front side with magnetic coating removed (substrate front side post deposition) has bumps and waviness. The backside of ME tape has no bumps and waviness, and this suggests that deformation of the front side is a local thermal effect. Table 2.2 gives roughness parameters for the substrate used to construct ME tape, ME tape and ME tape front side with magnetic coating removed from the tape. The substrate front side roughness parameters show that the substrate is much smoother than both the magnetic coating side of the tape and the tape front side with the magnetic coating removed, which both have similar roughness statistics. Thus, deposition of the magnetic coating increases roughness of the tape over that of the substrate. The post deposition substrate has higher roughness than the substrate front side which is an artifact of the substrate deformation which occurred during deposition of the magnetic coating. The back side of the substrate has
Figure 2.6. 3-D profiles from a NOP of ME substrate front side, ME tape magnetic coating side and ME tape front side with magnetic coating removed from the tape.
<table>
<thead>
<tr>
<th>Roughness parameter</th>
<th>Substrate front side</th>
<th>Tape magnetic coating side</th>
<th>Tape front side with magnetic coating removed</th>
<th>Substrate back side</th>
<th>Tape back side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rms surface height, nm</td>
<td>2.6</td>
<td>8.3</td>
<td>8.3</td>
<td>11</td>
<td>14</td>
</tr>
<tr>
<td>Rms profile slope x, mrad</td>
<td>0.58</td>
<td>0.83</td>
<td>0.78</td>
<td>4.2</td>
<td>11</td>
</tr>
<tr>
<td>Rms profile slope y, mrad</td>
<td>0.42</td>
<td>0.67</td>
<td>0.64</td>
<td>2.9</td>
<td>7.0</td>
</tr>
<tr>
<td>Rms surface slope, mrad</td>
<td>0.71</td>
<td>1.1</td>
<td>1.0</td>
<td>5.1</td>
<td>13</td>
</tr>
<tr>
<td>Rms profile curvature x, 1/mm</td>
<td>0.76</td>
<td>1.0</td>
<td>0.95</td>
<td>4.8</td>
<td>16</td>
</tr>
<tr>
<td>Rms profile curvature y, 1/mm</td>
<td>0.53</td>
<td>0.68</td>
<td>0.68</td>
<td>2.8</td>
<td>8.2</td>
</tr>
<tr>
<td>Rms surface curvature, 1/mm</td>
<td>0.48</td>
<td>0.62</td>
<td>0.60</td>
<td>2.9</td>
<td>9.0</td>
</tr>
<tr>
<td>Summit height(^b), nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>3.8!/5.7</td>
<td>6.1!/18</td>
<td>6.2!/15</td>
<td>22!/120</td>
<td>14!/58</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>3.1!/0.63</td>
<td>7.4!/2.3</td>
<td>6.5!/2.0</td>
<td>21!/15</td>
<td>13!/6.8</td>
</tr>
<tr>
<td>Summit slope(^b), mrad</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.10!/0.032</td>
<td>0.29!/0.33</td>
<td>0.16!/0.16</td>
<td>2.0!/7.6</td>
<td>7.9!/16</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.10!/0.014</td>
<td>0.34!/0.33</td>
<td>0.15!/0.16</td>
<td>2.8!/2.7</td>
<td>3.4!/4.1</td>
</tr>
<tr>
<td>Summit curvature(^b), 1/mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>1.8!/1.9</td>
<td>2.5!/3.5</td>
<td>2.4!/2.8</td>
<td>7.3!/40</td>
<td>9.0!/23</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.49!/0.32</td>
<td>1.1!/1.2</td>
<td>1.2!/1.6</td>
<td>6.4!/12</td>
<td>4.5!/7.1</td>
</tr>
<tr>
<td>Summit-to-valley distance, nm</td>
<td>25</td>
<td>70</td>
<td>71</td>
<td>230</td>
<td>165</td>
</tr>
<tr>
<td>Summit-to-mean distance, nm</td>
<td>14</td>
<td>31</td>
<td>30</td>
<td>140</td>
<td>75</td>
</tr>
<tr>
<td>Number of summits per square millimeter(^b)</td>
<td>150!/26</td>
<td>310!/53</td>
<td>230!/110</td>
<td>6700!/53</td>
<td>49000!/800</td>
</tr>
<tr>
<td>Profile zero crossings x, 1/mm</td>
<td>33</td>
<td>36</td>
<td>35</td>
<td>88</td>
<td>160</td>
</tr>
<tr>
<td>Profile zero crossings y, 1/mm</td>
<td>21</td>
<td>15</td>
<td>17</td>
<td>51</td>
<td>80</td>
</tr>
<tr>
<td>Average autocorrelation distance (μm)</td>
<td>33</td>
<td>33</td>
<td>34</td>
<td>11</td>
<td>16</td>
</tr>
</tbody>
</table>

\(^a\)Scan size for NOP is 250 × 250 μm

\(^b\)Mean and Rms values are given for all summits (first numbers) and summits with top 25% summit height (second numbers), and a threshold of 1.0 nm was used in defining summits on the surfaces

Table 2.2. Roughness data for the front side and back side of wavy non-DLC ME substrate and tape as measured with a NOP\(^a\).
higher roughness statistics than the front side, and application of the back coating by the tape manufacturer makes the tape back side rougher than the substrate back side.

Stiffness in the machine direction (MD) and transverse direction (TD) and thickness for selected tapes and substrates are given in Table 2.3 (Scott and Bhushan, 1997). The TD stiffness of ME tape is larger than that of the other tapes by about a factor of two. The stiffer anisotropic ME substrate has higher TD stiffness, whereas, the anisotropic MP substrate is tensilized PET with higher MD stiffness.

<table>
<thead>
<tr>
<th>Tape or substrate</th>
<th>Wavy non-DLC</th>
<th>ME substrate</th>
<th>MP substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD stiffness ((\mu)Pam(^3))</td>
<td>0.55</td>
<td>0.21</td>
<td>0.16</td>
</tr>
<tr>
<td>TD stiffness ((\mu)Pam(^3))</td>
<td>0.78</td>
<td>0.38</td>
<td>0.08</td>
</tr>
<tr>
<td>Thickness ((\mu)m)</td>
<td>10.8</td>
<td>9.8</td>
<td>8.7</td>
</tr>
</tbody>
</table>

Table 2.3. Stiffness and thickness data for selected magnetic tapes and substrates.

In section 3.3 of this dissertation, performance of ME tapes with various surface texture and the same lubricant thickness are studied along with ME tapes with various lubricant thickness and the same surface texture. ME tapes with various surface texture and the same lubricant thickness were used in performance tests to determine the effect of surface texture on tape performance. Various surface texture was obtained by varying the size and areal density of SiO\(_2\) particles added to the precoat on to the ME treated side of the base film. Table 2.4 gives SiO\(_2\) precoat particle size and areal density for each of the five tape samples. Samples one through three were used to study the effect of asperity density or the number of asperities on tape performance, whereas, samples three through five were used to study the effect of asperity size on tape performance. Thickness of the magnetic layer for the tapes is 130 nm. Since the tapes have the same magnetic coating with identical mechanical properties as well as the same lubricant thickness, any difference in the friction and wear performance can be attributed to varying surface texture. Identical lubricant thickness suggests that adhesion strength, which is based on
chemical interactions at a molecular scale, should not depend on surface texture and the adhesion component of friction should be proportional to the real area of contact. Surface topography of the virgin and used tapes was measured using an AFM. Scan sizes for AFM measurements were 1 × 1 μm and 10 × 10 μm with lateral resolutions of about 4 nm and 40 nm, respectively.

Table 2.4 gives rms surface height for each of the five virgin tape samples. At constant precoat particle size, higher precoat particle areal density increases rms surface height. At constant precoat particle areal density, higher precoat particle size increases rms surface height. A non-Gaussian surface may exhibit skewness (Sk) and kurtosis (K).

Skewness is a parameter which defines asymmetric spread of the surface height distribution and is given by

\[ Sk = \frac{1}{\sigma^3} \int_{-\infty}^{\infty} z^3 p(z) \, dz \tag{2.1} \]

where \( p(z) \) is the probability density function of height variable \( z \) and \( \sigma \) is the standard deviation of surface heights. A Gaussian surface has zero skewness. Kurtosis represents peakedness of the distribution and is given by

\[ K = \frac{1}{\sigma^4} \int_{-\infty}^{\infty} z^4 p(z) \, dz \tag{2.2} \]

A Gaussian surface has a kurtosis of 3. Table 2.4 gives skewness and kurtosis for each of the five virgin tape samples which are all non-Gaussian. Surfaces with positive skewness have more peaks above the mean than Gaussian surfaces. Surfaces with kurtosis greater than 3 have more peaks and valleys further from the mean than Gaussian surfaces. All of the virgin tapes have positive skewness and kurtosis. At constant precoat particle size, lower precoat particle areal density increases both skewness and kurtosis. At constant precoat particle areal density, lower precoat particle size increases both skewness and kurtosis.

ME tapes with various lubricant thickness and the same surface texture were also used in performance tests to determine the effect of lubricant thickness on tape performance. Relative lubricant thickness of the tapes are 1.0, 1.4 and 1.9. These tapes have a 180 nm thick Co_{80}Ni_{20} magnetic layer with organic particles added to the precoat on the ME treated side of the base film with a particle size of 100 nm and particle areal density of 5/μm^2. Some analyses that were performed on ME tapes with various surface texture were not performed on ME tapes with various lubricant thickness.

Figure 2.7 shows 3-D line and greyscale plots from an AFM of virgin ME tapes with 25 nm precoat particle size and various precoat particle areal density (in 1/μm^2) at a 10 × 10 μm scan size. For tapes with 25 nm precoat particle size, increasing precoat particle areal density increases the number of asperities on the surface. In the line plots,
distance between asperities decreases as precoat particle areal density increases, until at an overcoat particle areal density of 60/μm², individual asperities cannot be easily distinguished. In the greyscale plots, the number of bright spots (asperities) increases as precoat particle areal density increases, until at a precoat particle areal density of 60/μm², bright spots are very close to each other. From the greyscale plots, asperity diameter for tapes with 25 nm overcoat particle size varies from about 100 to 400 nm. The fact that asperity size is larger than the precoat particle size of 25 nm is due to a shadowing effect during deposition of the magnetic coating.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precoat particle size (nm)</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>Precoat particle areal density (1/μm²)</td>
<td>5</td>
<td>10</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Rms surface height (nm)</td>
<td>5.0</td>
<td>6.9</td>
<td>10.2</td>
<td>6.7</td>
<td>5.3</td>
</tr>
<tr>
<td>Surface skewness</td>
<td>2.1</td>
<td>1.3</td>
<td>0.0</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Surface kurtosis</td>
<td>10.5</td>
<td>4.3</td>
<td>2.3</td>
<td>4.5</td>
<td>4.1</td>
</tr>
</tbody>
</table>

Table 2.4. Substrate precoat particle size, areal density and various roughness parameters for virgin ME tapes used to study the effects of surface texture on tape performance.

Figure 2.8 shows 3-D line plots from an AFM of virgin ME tapes with a precoat particle size of 25 nm and various precoat particle density at a 1 x 1 μm scan size. Asperities on each tape surface generally have the shape of spherical caps. Asperities on the tape with a precoat particle areal density of 5/μm² are about the same size (100 to 200 nm wide), whereas, at higher precoat particle areal densities distribution of asperity size is bimodal with both smaller (100 to 200 nm wide) and larger (300 to 400 nm wide) asperities being present. Difficulty in dispersing or agglomeration of precoat particles at higher precoat particle areal densities is the likely cause of the bimodal distribution of particle sizes especially if one considers that the distribution of asperity size is not bimodal at a precoat particle areal density of 5/μm².
Figure 2.7. 3-D line and greyscale plots from an AFM of virgin ME tapes with various precoat particle size (in nm) and areal density (in 1/μm²) at a scan size of 10 × 10 μm.
Figure 2.8. 3-D line plots from an AFM of virgin ME tapes with a precoat particle size of 25 nm and precoat particle areal densities of 5, 10 and 60/μm² at a scan size of 1 × 1 μm.
Figure 2.7 shows 3-D line and greyscale plots from an AFM of virgin ME tapes with 60/μm² precoat particle areal density and various precoat particle size (in nm) at a 10 x 10 μm scan size. For tapes with 60/μm² precoat particle areal density, decreasing precoat particle size decreases the size of asperities on the surface. However, on the tapes with 12 and 18 nm overcoat particle size, there are a few large high isolated asperities on the tape surface that are most visible in the greyscale plots. The large high isolated asperities are probably due to agglomeration of precoat particles and are likely to affect tribological performance of the tapes. Large high isolated asperities on the 18 nm, 60/μm² tape generally have larger diameters than those on the 12 nm, 60/μm² tape. It was originally intended that the matrix of tapes with 60/μm² precoat particle areal density and various precoat particle size would be used to study the effect of asperity size on tape performance. However, high isolated asperities prevent this, and in essence, shifted the study to that of smooth surfaces with high isolated asperities.

Figure 2.9 shows bearing ratio plots from an AFM of virgin ME tapes with various precoat particle size and areal density at a of 10 x 10 μm scan size. Bearing ratio plots for tapes with extreme values of precoat particle size and areal density are shown to illustrate extreme effects of varying these quantities on the distribution of tape surface area with respect to the highest point on a given tape. At a precoat particle areal density of 60/μm², bearing ratio for the tape with a 25 nm precoat particle size begins a gradual increase at about 15 nm from the highest point on the tape, whereas, bearing ratio for the tape with a 12 nm precoat particle size begins a sharp increase at about 35 nm from the highest point on the tape. At a precoat areal density of 60/μm², the main effect of larger precoat particle size on bearing area is to provide more bearing area closer to the highest point on the tape, and to prevent most of the bearing area from being in a narrow range of distances from the highest point on the tape. At a precoat particle size of 25 nm, higher precoat particle areal density provides more bearing area closer to the highest point on the tape and spreads the bearing area over a larger range of distances from the highest point. The major difference in bearing ratio between the 12 nm, 60/μm² and 25 nm, 5/μm² tapes is the shoulder between 25 and 45 nm distance from the highest point on the tape for the 25 nm, 5/μm² tape (shoulder is not present for 12 nm, 60/μm² tape) which precedes the rapid increase in bearing ratio at 45 nm from the highest point. The shoulder is due to the larger number of high asperities for the 25 nm, 5/μm² tape, as compared to the 12 nm, 60/μm² tape, and is representative of the fact that more asperities are available for load bearing for the 25 nm, 5/μm² tape.
Figure 2.9. Bearing ratio plots from an AFM for virgin ME tapes with various precoat particle size and areal density at a scan size of 10 x 10 μm.
2.2.2 Linear Tape Drive

The sliding tests were conducted with Fuji Atomm double layer video grade (substrate/total thickness = 9.8/13.2 μm) MP tapes (rms = 4 nm, P-V = 37 nm) run against the heads. Two kinds of heads were used in the testing corresponding to studies of alternate pole tip materials in section 5.2 and hard carbon coatings in section 5.3. Details of coupon construction and mechanical property measurement techniques used for micromechanical characterization of alternate pole tip materials, which is presented in section 5.2.1, can be found in a previously published article (Patton and Bhushan, 1996c). In the remainder of this section, heads for experiments in section 5.2 will first be discussed followed by a discussion of heads for experiments in section 5.3.

This begins the discussion of heads used to study alternate pole tip materials in section 5.2. In a real thin-film head for ultra-high density recording, an inductive write and an MR read head are used in the head construction. Since PTR is a problem in inductive write heads, a dummy write head with two inductive thin-film structures was used in this study to obtain data on two structures in a single test. In the evolving technology defining the thin-film structure of inductive heads, the following structure is expected to be used in the next generation of heads: an undercoat of about 0.25 μm thick sputtered Al₂O₃ to provide a smooth surface for lithography and insulation for copper leads etc., two 2-μm thick pole tips (can be thinner for a high magnetic moment material) with a 0.25-μm thick Al₂O₃ gap between the poles and a sputtered Al₂O₃ overcoat (about 20-μm thick) for protection against lapping and handling. A number of copper coils on the order of 14 is expected to be used in the head structure. In the MR head structure, much thinner coatings of Al₂O₃, NiFe and shield material are used in the head construction. For the dummy heads used in this study, a thinner overcoat of 2 μm was used to reduce the processing time. It should be noted that PTR should be a function of the thicknesses of the various films in the head structure. Therefore, data reported in this dissertation should only be used for comparison of the PTR behavior of NiFe, CoZrTa and FeAlN, and should not be used to compare with PTR measured in thin-film structures with thicknesses that are different than those used in this dissertation.

Figure 2.10 (a) shows the head construction with two inductive write elements and an expanded view of the thin-film structure which emulates an inductive write element in a real head. The head substrate material is Al₂O₃-TiC, and two thin-film regions are part of the head structure. The thin-film structure includes insulating Al₂O₃ undercoat, Al₂O₃ gap and Al₂O₃ overcoat films as well as two metallic pole tip films, all of which is
sandwiched between Al₂O₃-TiC substrate. Three distinct kinds of heads were used in the tape drive tests, and they differed only in that each of either NiFe, CoZrTa or FeAlN was used as the pole material in each kind of head. Figure 2.10 (b) shows an optical micrograph of the thin-film structure and surrounding substrate for a virgin NiFe head. The excellent quality of the thin-film structure is evident in the micrograph.

Figure 2.11 shows the multi-step head fabrication method that was used to construct the heads. Each thin-film region was sputtered onto an Al₂O₃-TiC wafer. After thin-film deposition, the thin-film side of each wafer was then bonded with Ablebond 410-3 unfilled glue to an Al₂O₃-TiC end cap which formed one half of the head structure. To glue together the coated wafer and end cap, they were clamped together with steel clips and copper shims. The glue was then wicked into the holes in the end cap with a piece of wire which allowed the glue to flow to the interface and form a few tenths of a micron width glue line between the end cap and wafer. The glue joint was then cured in an oven for 3 hours at 75°C, followed by 16 hours in the oven at 110°C. The two halves of the head were back ground on their wafer side and bonded together with Ablebond 789-3 glue which formed the dual element head block. The back grinding was done with a 12.7 mm 700 grit diamond particle grinding wheel. Glue was applied to the wafer side of each block, and then they were placed together and moved about to smear the glue uniformly in the joint and to remove any air pockets before being clamped with steel clips and copper shims. The glue joint was then cured in an oven for 1 hour at 125°C. The head was then cross slotted with a thin blade (1000 grit diamond particle) grinding saw with a vertically reciprocating blade which formed the bleed slots. Head blocks were contoured using 40-50 μm diamond particles in an 8 mm radius contoured grinding wheel in the presence of grinding lubricant for the rough contour. This was followed by using a 2-4 μm diamond particle/resin in an 8 mm radius contoured grinding wheel, and finally the head was given a fine polish with 0.5 μm diamond lapping tape.

A special nitrogen lapping procedure was used to further lap in order to attain minimal initial PTR for the head samples. The heads were bonded adhesively onto a holding tool which was mounted into an alignment fixture designed to be used on a Honeywell tape transport. The pitch, roll and azimuth angles were adjusted to attain optimum compliance with the tape media. The wrap angle was adjusted by penetrating the head into a transparent tape which was mounted to a fixture that emulates the tape path in the Honeywell tape drive. The head penetration was increased until an observed interference pattern indicated that the entire ABS was in contact with the tape. The fixture was then mounted onto a specially designed tape drive with a special enclosure.
Figure 2.10. (a) Schematic of the head construction of dummy heads used in tape drive tests and an expanded view of the thin-film structure, and (b) representative optical micrograph of the thin-film structure and surrounding substrate for a virgin NiFe head.
Figure 2.11. Multi-step fabrication method used to construct the dummy heads used in tape drive tests (Courtesy of Matt Dugas of Advanced Research Corporation).
surrounding the head mounting region. This enclosure was filled with dry nitrogen when tape lapping the head samples which minimized the humidity inside of the enclosure. The finished head surface was obtained by running a 25.4-mm wide preconditioned 25 μm thick diamond lapping tape with an average particle size of 1 μm across the head. The lapping was performed at a tension of 3.8 N and a tape speed of 0.2 m/s for about 60 m. This special lapping procedure reduced the PTR from about 30 nm for both the NiFe and FeAlN heads to 22 nm and 9 nm for NiFe and FeAlN, respectively.

This begins the discussion of heads used to study hard carbon coatings in section 5.3. Al₂O₃-TiC and Ni-Zn ferrite heads (rms = 1.5 nm) with IBM 3480/3490 type of construction were selected for this study, Fig. 2.12. One of the two modules (19 mm × 3.8 mm) had the thin-film construction of an inductive write head, whereas, the second module was a dummy module. The radius of modules was 20 mm. Thick films of NiFe were electroplated and Al₂O₃ and thin films of NiFe were rf sputtered. Al₂O₃-TiC heads have two poles with thin-film structure, and Ni-Zn ferrite heads utilize a single pole tip (Fig. 2.12). The hard amorphous carbon (a-C) (also referred to as diamondlike carbon) coatings with 20 nm thickness were deposited by cathodic arc and ion beam deposition techniques (Bhushan et al., 1995). Nanoindentation hardness values of cathodic arc and ion beam carbon coatings are 38 and 19 GPa, respectively, whereas, hardness of commonly used sputtered carbon is about 15 GPa (Bhushan et al., 1995). The critical load required to damage cathodic arc and ion beam coatings in microscratch experiments is more than a factor of two higher than that of the sputtered coatings (Bhushan et al., 1995).

2.3 Methods and Procedures

2.3.1 Rotary Head Tape Drive

To study durability of the tapes, streaming mode and pause mode experiments in which the tapes were subjected to play/rewind cycling were conducted in a class 10,000 laboratory at a temperature of 22±1 °C and 45±5% RH. In streaming mode, there is tape motion and fresh tape is continually supplied to the rotary heads. In pause mode, there is no tape motion and the rotary heads pass over the same track on the tape over and over again. VCR heads were run-in for three days with the same kind of tape to be used in an experiment which allowed head shape and metal core recession to saturate (Tsuchiya and Bhushan, 1994; Patton and Bhushan, 1995). A virgin cassette was recorded for ten
Figure 2.12. Top view schematic of IBM 3480/3490 type of head and expanded view of the thin-film structure for each substrate.
minutes (about 9 m length of tape) in the VCR. The recorded pattern was a sine wave with a 0.6 μm recording wavelength. The 0.6 μm recording wavelength was used to attain high sensitivity of reproduced head output to changes in head-to-tape spacing. For streaming mode durability tests, it was then played back and rewound (which constitutes one play/rewind cycle) repeatedly. Friction force, rms head output and signal dropouts were measured on the same section of tape during selected play/rewind cycles (during play), and head and tape samples were observed periodically with an optical microscope. To ensure that changes in friction force, head output and signal dropouts resulted from tape wear as opposed to changes in head performance, reference measurements were made using a virgin cassette of the same kind of tape during a cycling experiment. It was determined that head performance did not change over the course of cycling experiments.

At selected numbers of play/rewind cycles, surface topography of a tape specimen was measured using a NOP. The scan size for NOP measurements was 250 × 250 μm with a lateral resolution of about 1 μm. Changes in head output level were correlated to changes in head-to-tape spacing using the reproduce Wallace equation, eq. (1.5). At a recording wavelength of 0.6 μm, a 1 dB increase in head output during playback corresponds to about 10 nm reduction in head-to-tape spacing based on the Wallace equation. With a power signal to noise ratio of about 40 dB and a measurement system resolution of 0.1 dB at peak power, the experimental measurement system can resolve a 1 nm change in head-to-tape spacing and therefore can resolve nanometer changes in tape topography due to tape wear. Signal dropouts were measured to determine interface stability and recording performance to bit level resolution. An experiment was stopped when the number of play/rewind cycles was 1000 or when a tape was worn to a failure condition, whichever occurred first. The criterion for tape failure was based on both magnetic and tribological considerations, and a tape was deemed to have failed when a large or sudden degradation in both magnetic and tribological performance occurred during an experiment.

For pause mode durability testing, the virgin tape was recorded and then rewound. The recorder was started in play mode and then placed in pause mode (tape motion was stopped). A tape was run for seven minutes in pause mode while measuring only friction force and head output. Head and tape samples were observed with an optical microscope after seven minutes of pause mode testing.

To study the effects of tape stiffness or anisotropy of mechanical properties of a tape on head wear, MD and TD stiffness of the tapes were measured and saturated or steady state head contours formed by the tapes were measured by AFM imaging. Bending
stiffness measurements of the tapes and selected tape substrates were made with a tape loop stiffness tester which generated a force versus displacement curve from which bending stiffness was calculated for the tapes and substrates (Scott and Bhushan, 1997). Tape specimens were cut in 8 mm x 8 mm squares and sandwiched between two glass slides to make loops in either the MD or TD. A linear stage with micrometer scale was used to press a tape segment against a microbalance which measured the contact force between the tape and microbalance. AFM was chosen over non-contact optical and stylus profilers because AFM can measure true level differences between dissimilar materials (optical interference techniques introduce phase shifts due to different indexes of refraction for unlike materials which causes measurement errors) and produces 3-D images unlike the stylus profiler which gives only 2-D line scans (Patton and Bhushan, 1995). AFM also has better lateral resolution (about 200 nm at a 50 x 50 μm scan size) than the other instruments. To measure head contour formed by each kind of tape, the heads were first run against an abrasive lapping tape (Sony V8-25CLH) for 20 s which formed the standard initial head contour. The lapping tape contains Fe2O3 particles with a mean particle size of about 400 nm and is produced in the same manner as particulate magnetic tapes but with larger surface roughness. To form the saturated head contour for each kind of tape, the heads were run against a given kind of tape continuously for 3 days in the ambient laboratory condition. Contour of a MIG head was then measured by AFM imaging. These experiments were also used to study metal core recession and stain formation on the various materials which comprise the composite MIG head. AFM imaging and an optical microscope were used to characterize stain formation on the heads, and metal core recession information was extracted from AFM images.

In section 3.3 of this dissertation, origins of friction and wear of ME tape was studied. In the experiments, a virgin cassette was recorded (a 0.9 μm wavelength sine wave) for ten minutes (about 9 m length of tape) in the VCR using VCR electronics and then rewound. It was then played back one time and friction force, rms head output and signal dropouts were measured during playback. Any point on the tape surface will experience only 4 head passes during record and playback (Osaki et. al., 1994). Wear of the tape is expected to be mild and subtle under these conditions. To determine if a tape was worn during record and playback, an AFM was used to measure surface topography of the virgin and used tapes. Using a Wallace factor of 100 to account for spacing loss during both record and playback, a 1 dB increase in head output during playback corresponds to about 9 nm reduction in head-to-tape spacing at a recording wavelength of
0.9 μm. Pause mode experiments were conducted with the tapes, but play/rewind cycling experiments were not.

In chapter 4 of this dissertation, environmental effects on ME and MP tape performance was studied. Streaming mode and pause mode experiments with ME and MP tapes were conducted under equilibrium and non-equilibrium conditions inside of an environmental chamber to determine the effects of specific humidity (SH = ratio of the weights of water vapor to dry air in the mixture) and temperature on tape performance. In equilibrium experiments, the given condition inside the environmental chamber is maintained at all times, whereas, the non-equilibrium experiments involve changing the humidity while the recorder is in play mode. The environmental chamber (Cincinnati Sub Zero model 27-CLH) is specified to control temperature to ±1 °C and relative humidity (RH) to ±1% RH. The VCR and tape samples were placed in the chamber at a given condition 24 hours prior to experimentation which allowed the components to come to equilibrium. This is particularly important so that the wound tape reels come to equilibrium. A special wiring harness was constructed which allowed the VCR to be controlled from a remote location outside of the chamber using control contacts. A temperature and humidity probe with an analog voltage output connected to the A to D converter was placed inside the chamber for non-equilibrium experiments.

Figure 2.13 shows locations of various experimental conditions (for streaming mode experiments) with respect to the data processing operating envelope in the SH-temperature plane. A few reference lines of constant RH and the saturation line are also shown in Fig. 2.13. The data processing operating envelope (shaded area in Fig. 2.13) is 15.6 to 32.2 °C and 20 to 80% RH with a maximum wet bulb temperature of 25.6 °C (SH = 0.021). In streaming mode, experiments were conducted at six different combinations of SH and temperature, and five of the conditions are within the data processing operating envelope. Pause mode experiments were conducted at design tension under equilibrium conditions in a broader envelope at temperatures ranging from 5 to 37.8 °C and relative humidity ranging from 20 to 80% RH. To study the effect of SH on tape performance, experiments were conducted at selected SH at constant temperature. To study the effect of temperature on tape performance, experiments were conducted at selected temperature at constant SH. At each of the six experimental conditions used for streaming mode experiments, a virgin tape was recorded and rewound and then friction force, rms head output and signal dropouts were measured during the first play/rewind cycle. A few non-equilibrium experiments were conducted to determine the real time response of tape performance to changes in SH at constant temperature. In these experiments, equilibrium
Figure 2.13. Locations of various experimental conditions with respect to the data processing operating envelope in the specific humidity-temperature plane.
was disturbed by modulating RH in one cycle of a square wave, and friction force and head output were measured throughout the experiment.

2.3.2 Linear Tape Drive

To study growth in PTR in thin-film inductive write heads with increased sliding distance, tape shuttle experiments were conducted in a class 10,000 laboratory at a temperature of 22±1 °C and 45±5% RH. In a typical experiment, PTR of a virgin head was measured with an AFM, and optical micrographs of the thin-film region of the head were also taken (mostly for hard carbon-coated heads). Tape was run over the head using the tape drive, and PTR was measured again and more optical micrographs were taken. This procedure was repeated until either 500 or 1000 km of tape had slid over the head.

For the heads used to study alternate pole tip materials in section 5.2, the 1 N tape tension and 3 m/s sliding velocity resulted in a coefficient of friction of 0.27. This is slightly less than the value of 0.32 for Al₂O₃-TiC against MP tape in an intimate contact under conditions which eliminated air bearing effect (Bhushan and Lowry, 1995). Thus, despite wrapping over 90% of the head in the present study, the low tension and high sliding velocity results in some air bearing effect being present at the test conditions. These tests were conducted with rather intimate contact of the tape and head surfaces for test durations of 1000 km under accelerated conditions.

The heads used to study hard carbon coatings in section 5.3 were run at 1.7 N tape tension and 3 m/s sliding velocity in the drive. In normal drive operation, the tape wraps 17° over the head and engages one half of the outer bleed slots (Fig. 2.12), which results in a flying height of less than 100 nm. In these experiments, about 90 percent of the outer bleed slots were engaged by wrapping the head to increase the minimum film thickness region (which may accelerate wear by particle entrapment) and to increase the friction force (which may accelerate wear). Data in Fig. 2.14 (a) shows an increase in both the friction force and coefficient of friction at large wrap angles. Since at low sliding velocity and high tape tension, the coefficient of friction is higher than that under the condition of entire slot engagement as shown in Figs. 2.14 (b) and 2.14 (c), it appears that air bearing effect is still present at the test conditions.

Emphasis of all wear experiments conducted with the linear tape drive is on measurement of growth of PTR with sliding distance. The pole tip recession of the virgin heads and worn heads at selected sliding distances was measured by AFM imaging. The AFM was chosen over non-contact optical and stylus profilers because the AFM can
Figure 2.14. Coefficient of friction and friction force at nominal experimental conditions for the IBM 3480/3490 type of head as a function of (a) wrap angle, (b) sliding velocity and (c) tape tension.
measure the true level differences between dissimilar materials (optical interference techniques introduce different phase shifts due to different indexes of refraction for unlike materials which causes errors) and produces 3-D images (stylus profiler gives only 2-D line scans). The AFM also has better lateral resolution (~ 80 nm at a 20 × 20 μm scan size) than the other instruments.

For recession measurements with heads used to study alternate pole tip materials in section 5.2, the head was placed on a linear (x, y) translation stage with micrometer scales. The AFM tip was located and brought into focus in an optical microscope. Using the y translation stage, the end of the head nearest the experimenter was moved into the focal plane of the AFM tip. The x translation stage was then used to move one of the thin-film regions directly below the AFM tip, and the y stage micrometer reading was recorded by the experimenter. The head was then drawn towards the experimenter a known distance, and the PTR was measured at that location. By always placing the same end of a head towards theirself, the experimenter can make measurements in about the same location on the head each time the head is mounted on the translation stage. The head was moved using the translation stage and AFM measurements on both thin-film regions were made at several locations to account for any variability in PTR across the tape width and along the tape sliding direction (Fig. 2.10). Little variation in PTR was found in either direction. Typically, measurements were made at 2, 5, 8, and 11 mm across the 12.7 mm tape contact region for both thin-film regions. The average value of pole tip recession was taken over each AFM image, and pole tip recession for a given condition is the average of the 8 measurements made on the thin film regions.

For recession measurements with heads used to study hard carbon coatings in section 5.3, the head was placed on a linear stage. A pole on one end was first located in an optical microscope, and then the other poles were located with respect to that pole. Typically, poles numbered 3, 7, 11 and 15 (out of 1 to 18) were imaged and photographed to account for any variability across the tape width (Fig. 2.12). Pole tip recession was referenced to the substrate nearest to the pole, and the average was taken over each pole. Pole tip recession for a given condition is the average over the four chosen poles.

At each measurement location, a 20 × 20 μm area (section 5.2) or 100 × 100 μm area (section 5.3) was imaged which contained the entire width of the thin-film region as well as the Al₂O₃-TiC substrate on either side. For these PTR measurements, the fast scan axis of the AFM tip was in the tape sliding direction (Figs. 2.10 and 2.12), and the fast scan rate was 1 Hz. Tilt of the sample with respect to the fast and slow scan directions (x and y directions) was removed manually by adjusting the pitch and roll...
angle orientations of the tip with respect to the head sample. This was done by adjusting the pitch angle while observing the raw unaltered $z$ versus $y$ (with $y$ as the fast scan axis) AFM signal for flatness, and then adjusting the roll angle while observing the raw unaltered $z$ versus $x$ (with $x$ as the fast scan axis) AFM signal for flatness. Tilt in both directions was removed in several iterations of the above procedure, and then data were collected at that location. Zeroth order flatten software correction was then used to display the data. Zeroth order flatten removes any offset between fast scan data lines by calculating an average offset height and the bringing all fast scan lines to the average offset height. This procedure ensures that no erroneous software corrections have altered the true surface profile which allows the true PTR to be measured for the head samples.
CHAPTER 3

FRICTION, WEAR AND DURABILITY OF ME AND MP TAPES IN A ROTARY HEAD TAPE DRIVE

Low friction and wear and high durability are required in almost all sliding interfaces. In ultrahigh-density recording systems, where a few nanometers of wear can render a device inoperable, good tribological performance is even more crucial. Using the power of the rotary head tape drive experimental system, ME tapes with various surface topography and with and without a DLC coating as well as MP tapes were tested for durability and to determine friction and wear mechanisms. Origins of friction and wear were determined for the thin metallic layer of ME tape by testing tapes with different size and number of surface asperities. By understanding the fundamental friction and wear mechanisms, wear resistant and low friction surfaces can be developed for sliding interfaces.

3.1 Background

3.1.1 Pause Mode and Streaming Mode

There is still debate as to which of the emerging tape technologies is best suited for use in the next generation of ultra high density tape recorders. The thin continuous reactively evaporated magnetic coating of ME tape has among its advantages: lower demagnetization fields, high packing density of magnetic material, good overwrite, high remanent magnetization, narrow isolated pulse width and high carrier to noise ratio at short recording wavelength (Kawana et al., 1995). Some disadvantages of ME tape include: asymmetric isolated pulse shape, susceptibility to corrosion, questionable durability, production complexity and high cost.
Recent advances in MP and barium ferrite (BaFeO) tape technologies have reduced advantages presented by ME tape (Shibata et al., 1992; Richter and Veitch, 1995; Saitoh et al., 1995; Sharrock and Carlson, 1995; Speliotis, 1995; Sugita et al., 1995). Innovations of reduced and more uniform particle size and a new double coating technology which makes possible ultra thin particulate magnetic coatings by utilizing a non-magnetic underlayer of fine particulates have led to dramatically improved short wavelength performance for MP and BaFeO tapes (Shibata et al., 1992; Saitoh et al., 1995). Double coating technology produces thin ultra smooth coatings for both MP and BaFeO tapes, and thus reduces spacing loss, demagnetization fields and isolated pulse width. BaFeO tape has the disadvantage of low remanent magnetization, but low medium noise results in high carrier to noise ratios at short recording wavelengths. Generally, ME and MP tapes are best suited for applications where system noise is dominant, and BaFeO tape is best suited for systems where medium noise is dominant and low carrier amplitude is not detrimental to system performance.

Pause mode performance of ME and MP tapes is well understood because several studies have investigated the performance of the tapes in pause mode (Vorme Wege and Hornbogen, 1988; Osaki et al., 1990; Osaki et al., 1992; Patton and Bhushan, 1995; Patton and Bhushan, 1996b). However, little is known about their streaming (play) mode performance which is the normal mode of operation and is pertinent to data processing applications. Wear mechanisms and key performance parameters may be different in streaming and pause modes due to the fact that there is tape motion in streaming mode. Tape wear generates debris which may cause head clogging and signal loss during streaming mode operation (Osaki et al., 1994). Performance of the tapes must not degrade when they are subjected to play/rewind cycling, if they are to be used in applications in which no loss of information is tolerable over the lifetime of the tape. Wear mechanisms of ME and MP tapes, which affect the magnetic performance of the tapes, must be better understood to further improve their reliability and performance. Detailed analyses of the interface components and elucidation of critical tribological mechanisms is needed to gain further understanding.

Commercially available ME tapes either have waviness or do not have waviness (are relatively flat) and generally have an about 10 nm thick diamondlike carbon (DLC) coating on top of the magnetic layer. In the case of flat ME tape with no DLC coating, removing waviness may change the friction and wear mechanisms of the tape which will affect magnetic performance of the tape. Application of a DLC coating to flat ME tape should also affect tribological and magnetic performance of the tape. Pause mode
performance of ME tapes with a DLC coating was found to be superior to non-DLC ME tape in previous studies (Osaki et al., 1993; Kawana et al., 1995).

Metal core recession (recession of the metal core from the ferrite air bearing surface) and head stains (tenaciously adherent films which are not easily wiped away with a cloth and solvent) increase the distance between a tape and read/write gap of a head transducer which results in signal loss. Previous studies showed that metal core recession depended on the relative wear rates of various head materials and the kind of tape being used in the tape drive (Tsuchiya et al., 1993; Tsuchiya and Bhushan, 1995). Experiments with an 8-mm camcorder which uses amorphous CoNbZr MIG heads showed that metal core recession reached a stable value in about 15 hours of streaming mode operation, and that ME tape caused larger metal core recession than MP and BaFeO tapes (Tsuchiya and Bhushan, 1994). However, these studies used a NOP to measure metal core recession, and the NOP cannot correctly determine level differences between dissimilar materials. In this dissertation, AFM imaging was used to correctly measure level differences between dissimilar materials or metal core recession caused by ME and MP tapes run against crystalline Sendust MIG heads. Head stains have a propensity to develop under low humidity and low tension conditions and are thought to protect against head wear or be more prevalent when head wear is low (Ota et al., 1991; Stahle and Lee, 1992; Bhushan and Hahn, 1995). Severity of head staining for MIG heads depends on the metal core material, the region of the composite head and the kind of tape (Bhushan and Hahn, 1995; Gupta et al., 1995; Tsuchiya and Bhushan, 1995). Generally, head stains may be composed of both organic and inorganic species and the film may be spotty to continuous in its coverage (Ota et al., 1991; Stahle and Lee, 1992; Bhushan and Hahn, 1995; Gupta et al., 1995; Tsuchiya and Bhushan, 1995). Experiments which utilized an optical microscope and an 8-mm camcorder which uses amorphous CoNbZr MIG heads showed that MP and BaFeO tapes caused head stains primarily on the metal core and glass surfaces, whereas, ME tape did not cause head stains (Bhushan and Hahn, 1995). However, the relative propensity of the tapes to stain Sendust MIG heads is not known and a more sophisticated technique of stain characterization using AFM imaging needs to be developed to further understand stain formation.

Users of video cassette recorders (VCRs), camcorders, R-DAT and other rotary head recorders may routinely use different kinds of magnetic tapes in their recorders. Past experiments with ME, MP and BaFeO tapes showed that the pause mode lifetime of a tape increased as a head ran-in with the same kind of tape (Vome Wege and Hornbogen, 1988; Patton and Bhushan, 1996b). Interchanging ME and particulate tapes (MP and
BaFeO) in a tape recorder caused excessive head and tape wear while a tape formed its preferred head shape in pause mode experiments (Patton and Bhushan, 1995). It is well known that for increased tape thickness or stiffness, there is a tendency for heads to be contoured with larger radii of curvature as compared to contours formed by thinner tapes (Mizoh et al., 1992; Rogers and Hinterregger, 1993). Previous studies showed that MP and BaFeO tapes formed similar head contours which had smaller radii of curvature than the respective contours formed by ME tape (Tsuchiya and Bhushan, 1994; Patton and Bhushan, 1995; Patton and Bhushan, 1996b). It has been suggested that anisotropy of mechanical properties in the MD and TD primarily determine head contour or worn head shape (Mizoh et al., 1991; Mizoh et al., 1992). It is important to determine how mechanical properties of the tapes influence head contour, if the problem of tape conformity to the heads upon interchanging tapes in a drive is to be solved by tailoring mechanical properties of the various tapes to be used in the drive.

The objective of this investigation was to study the friction and wear mechanisms of the tapes during pause mode and streaming mode operation and their interplay with the magnetic performance of the tapes. A new complimentary set of measurement techniques and analyses is presented to assess tape performance.

3.1.2 Origins of Friction and Wear of the Thin Metallic Layer of ME Magnetic Tape

Fundamental understanding of friction and wear mechanisms of ME tape must be attained to develop a low friction and wear resistant tape. Origins of friction and wear in sliding interfaces have fundamental scientific and technological importance. Mechanisms of friction and wear have intrigued scientists for hundreds of years, and implementation of methods for friction and wear reduction into machines and devices saves valuable energy and natural resources.

Optimization of surface texture and lubrication are viable methods to improve ME tape performance and durability. Surface texture can be adjusted by varying the size and areal density of particles included in the precoat applied on top of the ME tape base film (Chiba et al., 1989; Osaki, 1993; Patton and Bhushan, 1996b). By adjusting precoat particle size and areal density, and hence, surface asperity size and number, the nature of adhesive contacts formed between the head and tape surfaces, friction force and head-to-tape spacing should change. This would affect magnetic and tribological performance of the tapes. Archard was the first to suggest that plastic deformation of asperities could not be the universal rule, and that elastic contacts are possible at asperity tips. Amontons law...
could still be obeyed if the number of elastic contacts is large (Archard, 1957). It was shown that asperity deformation may be elastic or plastic, and depends on both mechanical properties and surface topography (Greenwood and Williamson, 1966). Deformation of an asperity will be elastic up to a critical load and strain, after which it will begin to have some plastic deformation. Surfaces in contact generally will have junctions with a range of strain conditions. If a surface has isolated high asperities, there will almost certainly be some plastic deformation (Greenwood, 1967). Surface topography has been shown to influence the real area of contact and friction force for CrO₂ magnetic tapes (Bhushan et. al., 1984). It was argued that contact junctions are primarily elastic, and that a rougher surface results in higher contact stress, less real area of contact and lower friction force. However, roughness of CrO₂ tapes ranged from about 15 to 130 nm rms, and the results may not be relevant to the much smoother ME tapes used in this dissertation.

Little is known about wear mechanisms at an asperity level in sliding contact interfaces. In sliding experiments with stainless steel rubbing against itself investigating sub-μm wear debris generation, the dominant wear mechanisms were found to be brittle fracture and plastic deformation combined with adhesive transfer (Xuan et. al., 1990). It was found in a previous study with ME tapes that individual asperities were progressively flattened as the number of head passes increased in pause mode wear tests (Osaki, 1993). In a previous study with particulate magnetic tapes in pause mode, friction force and shear stress acting on asperities increased with the number of head passes. This was explained by suggesting that plastic flow or creep of the tape binder increased the real area of contact (Osaki et al., 1992).

The effect of a non-Gaussian surface height distribution on the real area of contact for computer generated surfaces under normal loading conditions was determined in an earlier study (Bhushan and Chilamakuri, 1996). The numerical model that they used is based on a variational principle minimizing the total complimentary potential energy (Tian and Bhushan, 1996). They found that both skewness and kurtosis of the surface height distribution affected real area of contact, and they defined optimum ranges of skewness and kurtosis for low friction. In particular, they determined that surfaces with kurtosis greater than 5 should be used for low friction. In a study investigating the differences between two metal particle tapes exhibiting different stiction (static friction) behavior using the same numerical model, high kurtosis was found to give low contact area and stiction (Bhushan et. al., 1997). However, the effect of shear stress resulting
from friction force on real area of contact and possible brittle fracture of asperities and associated plowing by loose wear debris particles was not considered in the model.

Deformation of surface asperities between two contacting solids is intimately related to friction and wear phenomena in a sliding contact. It has been shown that both normal and tangential stresses play a part in the plastic deformation of contacting asperities in a sliding interface (McFarlane and Tabor, 1950; Courtney-Pratt and Eisner, 1957). Plastic flow of metallic contact junctions as a shear stress was applied increased real area of contact and friction force. This was observed experimentally and was explained using plasticity theory. The basic idea being that application of a shear stress necessitates reduction of the normal stress, and that real area of contact must increase to support the load. However, in the case of elastic solids application of a shear stress decreased real area of contact (Savkoor and Briggs, 1977). Depending on whether the nature of the contacts is plastic or elastic, behavior of the contacts when a shear stress is applied is different.

Loose wear debris particles in the contact interface have been associated with high friction force due to increased plowing and deformation in previous studies (Suh and Sin, 1981; Oktay and Suh, 1992). Generation of loose wear debris particles is problematic in the sense that wear coefficients for abrasive wear are about 100 times larger than those for adhesive wear (Suh, 1986). Plowing was found to be the dominant mechanism of friction in the boundary lubrication of metals (Komvopoulos et al., 1985). In previous studies using a rotary head VCR and magnetic tapes, presence of loose wear debris particles in the head-to-tape contact interface was found to increase friction force and tape wear in durability tests (Patton and Bhushan, 1997a). Thus, the mechanism of loose wear debris generation at an asperity level needs to be understood to design a low friction and wear interface.

The objective of this investigation was to determine the origins of friction and wear of the thin metallic layer of ME tape. The tapes were used in a rotary head VCR that was instrumented to measure friction force, head-to-tape spacing and the presence of loose wear debris particles in the head-to-tape contact interface. Surface topography of virgin tapes and tapes that were recorded and played back only one time was measured with an AFM to determine subtle origins of wear. Simple models of the effects of plastic deformation and brittle fracture on friction force were developed to determine origins of friction.
3.2 Pause Mode and Streaming Mode

3.2.1 Pause Mode

Figure 3.1 shows friction force and head output during pause mode testing in a dry condition with ME tapes with and without a DLC coating and MP tape. In pause mode, there is no tape motion and the rotary heads pass over the same track on the tape over and over again. ME tapes without a DLC coating lacked stability in friction and head output relative to that exhibited by DLC ME tape. Head output for non-DLC ME tapes showed a rapid increase to about +1 dB, implying a decrease in head-to-tape spacing of about 10 nm for a recording wavelength of 0.6 µm based on the Wallace equation. Since lubricant thickness for non-DLC ME tapes is about 10 nm, this implies that essentially all of the lubricant was removed from areas of the ME tape that were contacting the head surfaces. After lubricant depletion from the rubbing track, interaction of the rotary heads with the magnetic coating prevented the rapid increase in head output observed during lubricant removal and generated solid debris which, at this environmental condition, caused signal instability due to spacing loss upon traversing the tape contact region of the head surface. Friction force increased gradually throughout the tests. For DLC ME tape, head output increased slightly as the experiment progressed due to mild burnishing of the tape surface and friction force remained essentially constant. Thus, DLC coating prevented the signal loss and friction increase observed with non-DLC ME tapes by preventing the heads from contacting the metallic magnetic layer. It should be noted that there is no clear lubricant removal regime for DLC ME tape, and based on the eventual increase of head output to about 0.1 dB, lubricant thickness is about a nanometer or less. For MP tape, head output increased slightly as the experiment progressed due to mild burnishing of the tape surface, and friction force increased throughout the test.

3.2.2 Streaming Mode

Figure 3.2 shows friction force and head output during streaming mode testing with wavy non-DLC and MP tapes during the first play/rewind cycle. Modulation of the friction force with an amplitude and period of about 1 mN and 5 s, respectively, results from the oscillatory movement of the tape by the tension regulator of the VCR, and the head output is consequently modulated in phase with the friction force due to changes in head-to-tape spacing (high tension gives high output). This kind of measurement
Figure 3.1. Friction force and head output during pause mode testing with ME tapes with and without a DLC coating and MP tape at 32.2 °C and SH = 0.003 (note 0 dB is the initial playback rms voltage for each tape and vertical arrows in block for non-DLC ME tapes indicate tape failure). DLC tape provides a longer life in pause mode.
Figure 3.2. Friction force and head output during streaming mode testing with wavy non-DLC ME and MP tapes.
determines the friction force and head output level for a given number of play/rewind cycles. The friction force obtained with MP tape is larger than that of ME tape.

Figure 3.3 shows initial dropout frequency in various classes of dropouts for ME tapes with and without a DLC coating and MP tape during the first play/rewind cycle. The tapes were in a dropout condition less than 10% of the time which illustrates the intermittent nature of the wear events which caused the dropouts. Wavy ME tape without a DLC coating generally had a larger dropout frequency than flat ME tapes with and without a DLC coating for a given class of dropouts. For flat ME tapes, DLC coating generally produced dropout frequencies slightly larger than without DLC coating. Since the surface morphology of flat ME tapes with and without a DLC coating are essentially identical, higher dropout frequency of DLC ME tape must be caused by something other than surface morphology. Dropout frequencies for MP tape are comparable to flat ME tapes. For a given dropout depth, dropout frequency for MP tape always decreased with increased dropout duration, whereas, for ME tapes dropout frequency was largest for a dropout duration of 3-10 μs for 4-6 and 6-9 dB dropout depths. The operative dropout mechanism may be different for ME tapes as compared to MP tape. For a given dropout duration, dropout frequency generally decreased with increased dropout depth for all of the tapes. Considering spacing loss in both the recording and playback of signal at a 0.6 μm recording wavelength, the 4-6 dB and 20-50 μs class of dropouts corresponds to the head moving a distance of about 100-200 μm (at 3.8 m/s) and a head-to-tape spacing of about 20-40 nm, which corresponds well with the waviness of the wavy ME tape surface. Dropout frequency for wavy ME tape with no DLC coating reduced by three orders of magnitude in going from the 4-6 dB and 20-50 μs dropout class to the 4-6 dB and >50 μs dropout class. This suggests that surface features associated with a distance not exceeding about 200 μm on the tape surface, or the waviness of the ME tape surface, caused a high dropout frequency in the 4-6 dB and 20-50 μs dropout class. Dropout frequency for flat ME tapes and MP tape in the 4-6 dB and 20-50 μs class of dropouts were more than one and two orders of magnitude less than that of wavy ME tape with no DLC coating, respectively.

Figure 3.4 shows the effect of recording wavelength on the dropout frequency in various classes of dropouts for wavy non-DLC ME tape. For all classes of dropouts measured, increased recording wavelength decreased the dropout frequency in each class, which by the Wallace equation, suggests that spacing loss is a cause of dropouts. For a given class of spacing loss dropouts, the dropouts are associated with the tape being moved some characteristic distance away from a head for a characteristic time. Increasing
Figure 3.3. Dropout frequency in various classes of dropouts for ME tapes with and without a DLC coating and MP tape during the first play/rewind cycle in an ambient environment.
Figure 3.4. Dropout frequency in various classes of dropouts for wavy non-DLC ME tape at two different recording wavelengths during the first play/rewind cycle.
the recording wavelength will shift the dropouts due to the same spacing phenomena to lower dropout depths, which will reduce the number of dropouts in a given class from that obtained with the shorter recording wavelength. Similar results were obtained with MP tape. Thus, stability in head-to-tape spacing is more critical in ultrahigh-density recording systems with shorter recording wavelength.

Figure 3.5 shows the effect of subjecting the tapes to play/rewind cycling on dropout frequency in various classes of dropouts. In the classes of dropouts shown in Fig. 3.5, wavy non-DLC ME tape had higher dropout frequency which generally decreased less with tape wear than that observed with flat ME tapes and MP tape. Performance of flat ME tape without a DLC coating improved with use through 100 play/rewind cycles, and the improvement must have resulted from tape wear. However, at the tape failure condition at 350 play/rewind cycles, dropout frequencies increased sharply. The relative insensitivity of wavy non-DLC ME tape performance to tape wear suggests that the major cause of dropouts for this tape may be waviness of the tape surface, as opposed to wear debris of the tape. Flat DLC ME tape performance generally improved over the first 100 play/rewind cycles, and then either degraded or remained constant from 100 to 1000 play/rewind cycles. Tape failure occurred for wavy non-DLC ME tape at 840 play/rewind cycles, and there was an increase in dropout frequencies at the failure condition. As will be discussed later, tape failure for flat DLC ME tape occurred at about 400 play/rewind cycles, and dropout data taken at 1000 play/rewind cycles is after tape failure. Performance of MP tape improved with use, and the improvement must have resulted from tape wear. No tape failure was observed for MP tape through 1000 play/rewind cycles. Thus, MP tape had better dropout performance throughout the cycling experiments than ME tapes.

Figure 3.6 shows the effect of subjecting the tapes to play/rewind cycling on friction force and head output. For all of the tapes, there was an initial decrease in head output over the first few cycles. Debris on the tape surface generated by sliding action of the original asperities severed from the virgin tape during the record pass increased head-to-tape spacing by about 5 nm (head output decreased about 0.5 dB) over the first few cycles. For wavy ME tape with no DLC coating, flat ME tape with DLC coating and MP tape, head-to-tape spacing was larger than that during the first play/rewind cycle over the first 25 play/rewind cycles. However, head-to-tape spacing was larger than that during the first play/rewind cycle over the first 100 play/rewind cycles for flat ME with no DLC coating. Comparing wavy and flat ME tapes without a DLC coating, average contact pressure is higher for wavy ME tape because the normal load is supported at high
Figure 3.5. Dropout frequency in various classes of dropouts for ME tapes with and without a DLC coating and MP tape at various numbers of play/rewind cycles in an ambient environment.
Figure 3.6. Progression of friction force and head output during play/rewind cycling in an ambient environment with ME tapes with and without a DLC coating (note 0 dB is the playback rms voltage during the first play/rewind cycle for each tape).
localized locations on the tape surface. Higher contact pressure accelerated the debris generation process in the case of wavy non-DLC ME tape.

Head output for non-DLC ME tapes and MP tape eventually increased to about +1 dB or higher as the number of play/rewind cycles increased and the tapes were either worn to a failure condition or as the number of play/rewind cycles approached 1000. This indicates that head-to-tape spacing was reduced by about 10 nm or more from the beginning to end of the cycling tests. For ME tapes without a DLC coating, failure occurred at about 350 play/rewind cycles for the flat tape compared to about 800 play/rewind cycles for the wavy tape. Head output for flat ME tape with no DLC coating increased rapidly from 50 to 350 play/rewind cycles (failure) as a result of catastrophic abrasive wear. Head output for wavy ME tape with no DLC coating increased rapidly from 10 to 50 play/rewind cycles and then remained essentially constant through 600 play/rewind cycles. Waviness allowed some loose wear debris to settle away from high contact points on the tape surface where the debris were unable to abrade the tape which prevented catastrophic abrasion observed with flat ME tape with no DLC coating for which there was no such settling of wear debris away from the head-to-tape contact zone. Comparing flat ME tapes with and without a DLC coating, the DLC coating prevented rapid increase in head output observed without a DLC coating and head output was never much larger than it was during the first play/rewind cycle. After about 250 play/rewind cycles, head output for flat DLC ME tape decreased and became unsteady probably due to lateral crack formation which produced some loose wear debris.

All of the tapes showed a rapid increase in friction over the first few play/rewind cycles as shown in Fig. 3.6. Increased head-to-tape spacing for the tapes concurrent with the rapid increase in friction suggests that loose wear debris present on the tape surface caused increased friction force. Wear debris particles have been associated with high friction due to increased plowing in a previous study (Oktay and Suh, 1992). Comparing non-DLC ME tapes, friction force for flat ME tape increased nearly linearly until tape failure due to increased plowing by loose abrasive particles in the interface, whereas, friction force for wavy ME tape flattened out after about 50 play/rewind cycles due to abrasive particles settling away from high contact points and the onset of adhesive wear. In the case of flat DLC ME tape, friction force becomes essentially constant after 250 play/rewind cycles as the nature of the head-to-tape contact condition became that of the head sliding over coating shed which increased head-to-tape spacing.

Figure 3.7 shows the effect of subjecting the tapes to play/rewind cycling on head output and dropout frequency. For wavy non-DLC ME tape, the 6-9 dB and 3-10 µs
Figure 3.7. Progression of head output and dropout frequency during play/rewind cycling in an ambient environment with ME tapes with and without a DLC coating and MP tape (note 0 dB is the playback rms voltage during the first play/rewind cycle for each tape).
dropout frequencies remained constant or decreased until head output began to increase at which time they also began to increase due to catastrophic abrasive wear. For flat DLC ME tape, 6-9 dB and 0.5-3 μs dropouts decreased until tape failure at about 400 play/rewind cycles at which time they increased and became unstable as head-to-tape spacing increased due to coating shed in the contact interface. In the case of MP tape, dropout frequencies generally decreased as the tape was worn smooth. From about 300 play/rewind cycles through the completion of the experiment, dropout frequencies and head output shown in Fig. 3.7 for MP tape have reached saturated values. The saturated value of head output corresponds to about 15 nm reduction in head-to-tape spacing and the reduction in spacing produced greater stability of the head-to-tape interface based on decreased dropout frequencies.

Optical micrographs of virgin and worn tape surfaces are shown in Fig. 3.8. The worn condition for wavy and flat ME tapes without a DLC coating, flat ME tape with a DLC coating and MP tape correspond to 840, 350 and 1000 play/rewind cycles, respectively. All of the worn ME tapes have lateral cracks across each tape surface. In a previous study where a nickel film was deposited on a polymer substrate, the nickel film was found to crack in a brittle fashion with cracks being transverse to an applied longitudinal strain (Guo et al., 1990). For wavy non-DLC ME tape, one end of a lateral crack generally was located on a localized damage area and the other end on an adjacent (across the tape width) localized damage area and a crack often propagated through defects in the magnetic coating. For flat ME tapes with and without a DLC coating, lateral cracks often propagated through defects in the magnetic coating and in some cases terminated at a defect site. Damage areas are seen on the worn MP tape surface which is consistent with the 15 nm reduction in head-to-tape spacing over the cycling test.

Wear mechanism for wavy non-DLC ME tape is different than that of flat ME tapes with and without a DLC coating. In the worn condition for wavy non-DLC ME
Figure 3.8. Optical micrographs of virgin and worn tape surfaces for ME tapes with and without a DLC coating.
tape. localized wear occurred at high contact points due to high contact pressure, whereas, for flat ME tapes with and without a DLC coating no such localized wear occurred because the tapes contacted the heads more uniformly over a larger area which reduced contact pressure. The tape surface between localized damage areas at 840 play/rewind cycles for wavy non-DLC ME tape appears to be identical with the virgin surface of the tape (with the exception of the lateral cracks) which suggests that these regions had little or no interaction with the rotary heads. With the exception of the lateral cracks, damage to flat ME tapes with and without a DLC coating is not visible in micrographs of the worn tape surfaces.

Detailed analyses of virgin and used head and tape samples was conducted in experiments with wavy ME tape without a DLC coating and MP tape. The analyses, which support proposed friction and wear mechanisms, will be presented subsequently and will continue to the end of this section. Optical micrographs in Fig. 3.9 of the head surfaces after running against wavy non-DLC ME and MP tapes for various numbers of play/rewind cycles show that loose wear debris was transferred to the leading edges from the tape and collected on the trailing edges of the tape contact regions of the head surfaces. In a previous study using the same tapes in pause mode, chemical analyses showed that loose wear debris consisted of tape binder for particulate tapes and topical lubricant and magnetic coating for ME tape (Patton and Bhushan, 1996b). Prior to running for seven minutes at each condition, the heads were wiped clean of any loose debris with a lint free cloth soaked in isopropyl alcohol. Thus, the amount of loose wear debris transferred to the heads at each condition gives insight into the amount of tape wear and the amount of loose wear debris present on the tape surface. The amount of loose wear debris collected on the leading and trailing edges of the tape contact regions of the head surfaces was largest during the recording pass which suggests that much debris was generated in the head-to-tape interface in the first tape pass. For both wavy non-DLC ME and MP tapes during play/rewind cycling, the amount of loose wear debris transferred to the head surfaces generally decreased from the record pass through the end of the cycling experiment. However, there was a tendency for loose wear debris to agglomerate into larger flake-like particles at larger numbers of play/rewind cycles (particularly for MP tape) which is indicative of an adhesive wear mechanism, which may explain why dropout classes of larger time duration increased with tape wear as shown in Fig. 3.5. Aside from the record pass in which there was excessive transfer of loose wear debris to the head surfaces from MP tape, wavy non-DLC ME and MP tapes transferred similar amounts of loose wear debris to the head surfaces.
Figure 3.9. Optical micrographs (from top to bottom at each condition) of the flying erase ferrite head, an MIG read/write head and magnified views of the head gap region, the leading edge and the trailing edge for MIG read/write heads all run against wavy non-DLC ME and MP tapes in streaming and pause modes for seven minutes under various conditions. Note that the head was wiped clean prior to the seven minutes running at each condition.
In pause mode for each kind of tape, there was more loose wear debris transferred to the head surfaces than in streaming mode except for in the case of the record pass for the tapes. For wavy non-DLC ME tape in pause mode, lubricant was transferred to the heads and collected in pools of liquid on the trailing edges of the tape contact regions which was not observed in streaming mode. The fact that much loose wear debris transferred to the head surfaces from MP tape in pause mode is surprising since head output data in Fig. 3.1 shows that reduction in head-to-tape spacing was only 1 or 2 nm during the experiment. Pause mode debris for MP tape is flake-like which again is indicative of an adhesive wear mechanism.

Optical micrographs in Fig. 3.10 of the tape surfaces show the progression of wear for wavy non-DLC ME and MP tapes after various numbers of play/rewind cycles and after seven minutes of pause mode testing. For both wavy non-DLC ME and MP tapes during play/rewind cycling, the amount of tape wear increased from the record pass through the end of the cycling experiment as head-to-tape spacing was reduced in each case. Tape wear initiated at high localized contact locations and is first visible after 10 play/rewind cycles as damage areas for wavy non-DLC ME tape and impressions or "footprints" of rolling particles and high aspect ratio elliptical shaped damage areas for MP tape. The larger and sharper asperities of MP tape, when severed from the tape surface and located in the contact interface, rolled in the interface as rigid bodies due to their irregular shape and caused impact wear (Bhushan and Patton, 1994). The sliding and rolling action of loose wear debris on the tape surface on and near the damage points, and the fact that the initial damage occurred at the highest summits or load bearing asperities, led to growth in the size of the damaged areas with further play/rewind cycling as head-to-tape spacing became smaller. In an earlier study, it was estimated that a loose abrasive particle may spend 90% of its time rolling and 10% of its time sliding or abrading the surfaces (Rabinowicz et al., 1961). It should be noted that the percentage of time that a particle rolls in the interface should depend on the size and shape of the particle, and that a particle may wear the surfaces by impacting them even while rolling. Thus, in going from 10 to 100 and 100 to 1000 play/rewind cycles, existing damage areas grew in size and new damage areas were created as the tape was worn smooth which allowed further reduction in head-to-tape spacing which caused additional damage. As the elliptical wear scars became larger at higher numbers of play/rewind cycles, it is evident in Fig. 3.10 that the semi-major axes of the ellipses are along the head running direction.

Waviness played a role in the wear mechanism for wavy non-DLC ME tape, whereas, the relative flatness of MP tape led to different wear behavior. For wavy non-
Figure 3.10. Optical micrographs showing progression of wear of the wavy non-DLC ME and MP tape surfaces after the record pass, after various numbers of play/rewind cycles and after seven minutes of pause mode testing.
DLC ME tape, damage caused by the rotary heads occurred at a smaller number of discrete locations per unit area than that present on the MP tape surface. After 100 play/rewind cycles, damage was present at two discrete locations for wavy non-DLC ME tape, whereas, damage was present at about ten discrete locations for MP tape as shown in Fig. 3.10. After about 1000 play/rewind cycles, damage to the wavy non-DLC ME tape surface was more localized than that present on the MP tape surface. The tape surface between localized damage areas after 840 play/rewind cycles for wavy non-DLC ME tape appeared to be identical with the virgin surface of wavy non-DLC ME tape (with the exception of the lateral cracks) which suggests that these regions had little or no interaction with the rotary heads. The damage to MP tape was more widespread after 1000 play/rewind cycles, and most of the surface looks like it had interaction with the rotary heads due to the presence of wear scars.

On the wavy non-DLC ME tape surface, damage initiated at high points or bumps which were caused by thermal damage to the substrate during deposition of the magnetic coating. The initial and highest localized damage regions were about 250 μm apart which correlates well with waviness of wavy non-DLC ME tape. A large number of cracks formed and connected localized damage areas at tape failure after 840 play/rewind cycles. A relatively small number of lateral cracks were first observed on the wavy non-DLC ME tape surface after 100 play/rewind cycles as shown in Fig. 3.10. At the tape failure condition after 840 play/rewind cycles, one end of a lateral crack generally was located on a localized damage area and the other end on an adjacent (across the tape width) localized damage area. The cracks often propagated through a defect in the magnetic coating and in some cases terminated at a defect site. The lateral nature of all of the cracks suggests that the crack driving force was probably longitudinal tension maintained in the tape by the tape transport, since the most common mode of cracking or the tensile mode is the opening or separation of material by the maximum tensile stress which acts in a plane normal to the applied force (Timoshenko and Young, 1968; Hertzberg, 1989).

Tables 3.1 and 3.2 give roughness data for wavy non-DLC ME and MP tapes used in play/rewind cycling experiments as measured with a NOP. The NOP was selected for tape wear measurements due to the intermittent nature of wear on the tape surfaces. The 250 × 250 μm scan size of the NOP is large enough to ensure that roughness statistics do not critically depend on the location of a measurement with respect to a given damage area on the tape surface while still giving a micron of lateral resolution. The ease and simplicity of use of the NOP can expedite getting adequate sample statistics which requires taking numerous measurements on each tape sample. Data given in Tables 3.1

68
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<th>After play/rewind #100</th>
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\(^{A}\)Scan size for NOP is 250 x 250 \(\mu\)m

\(^{B}\)Mean and Rms values are given for all summits (first numbers) and summits with top 25% summit height (second numbers), and a threshold of 1.0 nm was used in defining summits on the surfaces

* Not enough summits in the top 25% of summit heights for partial statistics to be calculated

Table 3.1. Roughness data for wavy non-DLC ME tape used in play/rewind cycling experiments as measured with a NOP\(^{A}\).
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<td>53</td>
</tr>
<tr>
<td>Profile zero crossings y, 1/mm</td>
<td>40</td>
<td>39</td>
<td>45</td>
<td>38</td>
<td>58</td>
</tr>
<tr>
<td>Average autocorrelation distance (mm)</td>
<td>27</td>
<td>28</td>
<td>29</td>
<td>29</td>
<td>26</td>
</tr>
</tbody>
</table>

\(^a^\)Scan size for NOP is 250 x 250 \(\mu\)m

\(^b^\)Mean and Rms values are given for all summits (first numbers) and summits with top 25% summit height (second numbers), and a threshold of 1.0 nm was used in defining summits on the surfaces.

Table 3.2. Roughness data for MP tape used in play/rewind cycling experiments as measured with a NOP\(^a\).
and 3.2 are the average of measurements made at ten different locations on each tape surface. At each measurement location, twelve measurements were taken and averaged to arrive at each roughness parameter.

Roughness measurements were made on virgin tapes and on tapes at various stages of the cycling experiments. Roughness measurements were not made on tape samples used in pause mode experiments because the narrow (less than 50 μm wide) wear track and mild intermittent nature of the wear were not conducive to getting any meaningful statistics for the roughness parameters. The roughness of the tapes changed as the tapes were used and consequently worn. The evolution of roughness parameters was different for wavy non-DLC ME and MP tapes which suggests that wear mechanisms were different for the tapes. Generally, roughness parameters for summits changed by higher percentages than those of the entire surface because localized wear occurred on high load bearing summits.

Both wavy non-DLC ME and MP tapes were worn during the record pass. The data suggest that the highest summits on each tape surface were removed during the record pass. Surface slope, surface curvature, summit slope and summit density all decreased for the tapes in going from virgin to after the record pass. Thus, during the record pass many high asperities were removed from the tape, and as shown in Fig. 3.9 much loose wear debris was transferred to the heads during the record pass. Many severed asperities likely remained on the tape surface because it is unlikely that they all transferred to the head surfaces.

For wavy non-DLC ME tape during the cycling experiment, roughness parameters in Table 3.1 remained about the same from the record pass through 100 play/rewind cycles. The highly intermittent and localized nature of the wear of ME tape over the first 100 play/rewind cycles as seen in Fig. 3.10 is responsible for the unchanging roughness parameters through the first 100 play/rewind cycles. Surface height, surface slope, surface curvature, summit slope, summit-to-valley distance and summit density increased sharply after 840 play/rewind cycles and tape failure. The sharp increases in roughness parameters at tape failure is a measure of the catastrophic crack formation which connected heavily worn bumps on the ME tape surface and grossly deformed the surface.

For MP tape during the cycling experiment, surface slope, surface curvature, summit slope and summit density all evolved in a similar manner. After 10 and 100 play/rewind cycles, roughness parameters were larger than after the record pass. Loose wear debris located near localized high summits accelerated the wear process by rolling and sliding in the interface, and loose wear debris on the tape surface caused high...
roughness parameters after 10 and 100 play/rewind cycles. Evidence that the tape was pushed away from the heads by loose wear debris on the tape surface during the first 25 play/rewind cycles is given in Figs. 3.6 and 3.7. The fact that roughness data indicate that loose wear debris was present on the tape surface after 100 play/rewind cycles does not contradict the fact that head output had increased to +1 dB, since considerable wear of high points on the tape had occurred which allowed reduction in head-to-tape spacing. Loose wear debris present on the MP tape surface from 10 to 100 play/rewind cycles caused the initial rapid increase in friction force shown in Fig. 3.6. After 1000 play/rewind cycles, roughness parameters decreased to about the same values that they had after the record pass. Thus, loose wear debris was removed from the tape surface and high summits were worn smooth between 100 and 1000 play/rewind cycles which allowed reduction in head-to-tape spacing and the tape attained great running stability during streaming mode operation. Head output data in Figs. 3.6 and 3.7 for MP tape reached a saturated value after about 300 play/rewind cycles which suggests that virtually no tape wear occurred from 300 play/rewind cycles to the end of the experiment when little loose wear debris was present on the tape surface. Wear mechanism for the tape was abrasive over the first 300 play/rewind cycles due to loose wear debris on the tape surface, and wear mechanism was adhesive thereafter when little loose wear debris was present on the tape surface. It is known that wear coefficients for abrasive wear are about 100 times larger than those for adhesive wear (Suh, 1986).

Figure 3.11 shows summit density for virgin and worn MP tape as measured with a NOP and presented in Table 3.2. Summit density for MP tape was sensitive to tape wear. High summits were removed during the record pass, and summit density was high after 10 and 100 play/rewind cycles when an abrasive wear mechanism was operative. However, after 1000 play/rewind cycles summit density was again low and the wear mechanism was adhesive. Particulate barium ferrite tape exhibited similar behavior in summit density, and this data were presented elsewhere (Patton and Bhushan, 1998a).

Figure 3.12 (a) shows a schematic illustration of the evolution of tape wear and head-to-tape contact condition during play/rewind cycling with wavy non-DLC ME tape. High asperities on the virgin tape were severed off during the record pass and many remained on the tape surface as loose wear debris. During the 1st play/rewind cycle, the recording head slides across the tape surface at velocity \( v_h \) and \( d_1 \) is the distance between the recording head and the backside of the tape. Head-to-tape spacing during the 10th play/rewind cycle increased by 2 nm (head output dropped 0.2 dB) due to presence of
Figure 3.11. Summit density (for summits with top 25% summit height) for virgin and worn MP tape as measured with a NOP (note that the first data point is for virgin tape and the second data point is for after the record pass).
more loose wear debris generated by sliding action of the original asperities severed from the virgin tape, and friction force was higher than during the first play/rewind cycle due to increased plowing in the interface. During the 200th play/rewind cycle, loose wear debris on the tape has settled down away from high contact points, where it was unable to accelerate the wear process by plowing and wear mechanism is adhesive. Finally, head-to-tape spacing decreased another 2 nm and cracks are present at 840 play/rewind cycles and tape failure.

Figure 3.12 (b) shows a schematic illustration of the evolution of tape wear and head-to-tape contact condition during play/rewind cycling with flat non-DLC ME tape. High asperities on the virgin tape were severed off during the record pass and many remained on the tape surface as loose wear debris. Head-to-tape spacing during the 10th play/rewind cycle increased by 3 nm (head output dropped 0.3 dB) due to presence of more loose wear debris generated by sliding action of the original asperities severed from the virgin tape, and friction force was higher than during the first play/rewind cycle due to increased plowing in the interface. The contact condition during the 100th play/rewind cycle is similar to that of the 10th play/rewind cycle, except for the presence of more loose wear debris based on higher friction force and increased head-to-tape spacing. Finally, head-to-tape spacing decreased to a value about 9 nm less than during the 1st play/rewind cycle due to abrasive wear and cracks are present at 350 play/rewind cycles and tape failure.

Figure 3.13 shows a schematic illustration of the evolution of tape wear and head-to-tape contact condition during play/rewind cycling with flat DLC ME tape. High asperities on the virgin tape were severed off during the record pass and many remained on the tape surface as loose wear debris. Head-to-tape spacing during the 10th play/rewind cycle increased by 3 nm (head output dropped 0.3 dB) due to presence of more loose wear debris generated by sliding action of the original asperities severed from the virgin tape, and friction force was higher than during the first play/rewind cycle due to increased plowing in the interface. The contact condition during the 50th play/rewind cycle is similar to that of the 10th play/rewind cycle. Finally, head-to-tape spacing increased by about 20 nm due to shedding of the DLC coating and cracks are present at 1000 play/rewind cycles.

Figure 3.13 shows a schematic illustration of the evolution of tape wear and head-to-tape contact condition during play/rewind cycling with MP tape. High asperities on the virgin tape were severed off during the record pass and many remained on the tape surface as loose wear debris. During the 1st play/rewind cycle, the recording head slides
Figure 3.12. Schematic illustrations of the evolution of tape wear and head-to-tape contact condition during play/rewind cycling with wavy ME tape with no DLC coating and flat ME tape with no DLC coating.
Figure 3.13. Schematic illustrations of the evolution of tape wear and head-to-tape contact condition during play/rewind cycling with flat ME tape with a DLC coating and MP tape.
across the tape surface at velocity $v_h$ and $d_1$ is the distance between the recording head and the back side of the tape. Head-to-tape spacing during the 10th play/rewind cycle increased by 5 nm (head output dropped 0.5 dB) due to presence of more loose wear debris generated by sliding action of the original asperities severed from the virgin tape, and friction was high due to increased plowing in the interface. The contact condition during the 100th play/rewind cycle is similar to that of the 10th play/rewind cycle except for the fact that head-to-tape spacing decreased by 15 nm due to abrasive wear. Finally, head-to-tape spacing decreased another 5 nm and the amount of loose wear debris is low again at 1000 play/rewind cycles. At this point, wear mechanism is adhesive and any remaining blunt and flake-like loose wear debris is unable to abrade the tape surface.

Wear mechanisms of the tapes appear to be different in pause mode as opposed to streaming mode. Since there is no tape motion in pause mode, the rotary heads pass over the same track on the tape over and over again, and consequently tape damage is confined to a rectangular area along the head running direction with a width necessarily less than that of the video heads. This is evident in Fig. 3.10 for wavy non-DLC ME tape which was worn more in pause mode than MP tape. Waviness played a role in the wear mechanism of wavy non-DLC ME tape in pause mode. The optical micrograph in Fig. 3.10 shows that damage is more severe at two discrete locations (high points) along the rubbing track. High contrast of the head rubbing track with respect to the unworn region is probably a result of lubricant being depleted by transfer to the video heads which exposed the bare metallic magnetic coating. This contrast is not observed with wavy non-DLC ME tape in streaming mode where there is no evidence of lubricant depletion. This interpretation is consistent with data shown in Figs. 3.1 and 3.9 of this dissertation.

The wear scar on MP tape after seven minutes of pause mode operation is barely discernible in the optical micrograph in Fig. 3.10, and this is consistent with head output data in Fig. 3.1 which suggests that head-to-tape spacing was reduced by only about 1 or 2 nm during seven minutes of pause mode operation. The relatively mild wear of MP tape in pause mode as compared to streaming mode is of interest. It is known that small changes in operating conditions of an interface can change the wear mechanism (Bowden and Tabor, 1950). Tension and normal load in pause mode are about one half of their values in streaming mode which may decrease wear or change the wear mechanism. In streaming mode, the heads contact a larger surface area of tape than in pause mode, and consequently, wear of a given area of tape is influenced by wear debris from other areas of the tape surface. In pause mode, if an abrasive particle was expelled from the rubbing
track, then it could no longer abrade the tape surface. This is not true in streaming mode where the tape moves.

A relationship between wear coefficients in streaming and pause modes can be developed using the Archard wear equation. The Archard wear equation is

\[ V = kW x/H \]  

(3.1)

where \( V \) is the wear volume, \( k \) is the wear coefficient, \( W \) is the normal load, \( x \) is the sliding distance and \( H \) is the hardness of the softer material (in this case the tape). Equation (3.1) was developed for adhesive wear, but abrasive wear also follows it reasonably well (Archard, 1953; Suh, 1986). Using a simple analysis of a tape sliding over a curved surface, the expression for the normal load is

\[ W = T L/R \]  

(3.2)

and

\[ \mu = F/W = F R/(T L) \]  

(3.3)

where \( \mu \) is the coefficient of friction, \( F \) is the friction force, \( R \) is the radius of curvature of the curved surface, \( T \) is the tape tension and \( L \) is the length of the chord which has end points at either end of the tape contact region of the head surface.

Optical micrographs in Fig. 3.9 show that the contact length did not change in going from streaming mode to pause mode based on the location of debris on the head surfaces (contact area should be clean). Thus, the factor \( R/L \) will be the same in streaming and pause modes. If we assume that there is little air bearing effect at the head-to-tape interface (head and tape are in contact), then

\[ \mu_s = \mu_p \]  

(3.4)

where subscripts \( s \) and \( p \) refer to streaming and pause modes, respectively. Now, using eqs. (3.3) and (3.4) we get

\[ F_s/T_s = F_p/T_p \]  

(3.5)

Since we directly measured \( F_s \) and \( F_p \), a relationship between \( T_s \) and \( T_p \) can be determined.

For a given data track of width \( w \) and length \( l \) on the tape, the wear volume is

\[ V = -w l \alpha \Delta d \]  

(3.6)

where \( \Delta d \) is the change in physical spacing between the head and tape surfaces obtained from the Wallace equation and \( \alpha \) is the fractional contact area. Note that \( \alpha \) is an increasing function of normal load and consequently \( \alpha_s > \alpha_p \) (Bhushan, 1996). The sliding distance \( x \) for the tape in eq. (3.1) can be determined for streaming and pause modes in the following way. The rotary drum of the VCR spins at 30 Hz. In pause mode, there are three head passes per drum rotation, and for instance, in a seven minute pause
mode experiment there are 37,800 head passes. In streaming mode, there are two head passes per play/rewind cycle, and for instance, in 1000 play/rewind cycles there are 2000 head passes.

A relationship between the wear coefficients in streaming and pause modes can now be determined. We can rewrite eq. (3.1) using eq. (3.2) as

\[ V = \frac{k T L x}{(H R)}. \]  

(3.7)

H, R and L are the same in streaming and pause modes and from eq. (3.7) we get

\[ \frac{V_s}{V_p} = \frac{k_s T_s x_s}{(k_p T_p x_p)}. \]  

(3.8)

Using eqs. (3.5) and (3.6) in eq. (3.8) and solving for \( k_s/k_p \) gives

\[ \frac{k_s}{k_p} = \frac{\Delta d_s F_p x_p \alpha_s}{(\Delta d_p F_s x_s \alpha_p)}. \]  

(3.9)

Equation (3.9) will be evaluated for MP tape using pause mode data from Fig. 3.1 and streaming mode data from Fig. 3.6 and the Wallace equation to determine \( \Delta d_s, \Delta d_p, F_p \) and \( F_s \). The entire 420 seconds of pause mode data will be used in eq. (3.9), but only the first 300 play/rewind cycles of streaming mode data over which tape wear occurred due to an abrasive wear mechanism will be used in eq. (3.9). This gives

\[ \frac{(k_s)_{MP}}{(k_p)_{MP}} = \frac{[(15 \text{ nm})(5.5 \text{ mN})(37,800 \alpha_s)]}{[(1.5 \text{ nm})(9 \text{ mN})(600 \alpha_p)]}. \]  

(3.10)

Using the fact that \( \alpha_s > \alpha_p \) and solving for \( (k_s)_{MP} \) gives

\[ (k_s)_{MP} > 385 (k_p)_{MP}. \]  

(3.11)

This result shows that wear coefficient during the time that abrasive wear occurred in streaming mode is over two orders of magnitude larger than the wear coefficient for adhesive wear in pause mode. In streaming mode, wear of a given area of the tape is influenced by loose wear debris from other areas of the tape which allowed abrasive wear to occur over the first 300 play/rewind cycles. However, abrasive particles expelled from the wear track in pause mode could no longer contribute to tape wear and wear mechanism was adhesive which explains large differences in wear rates observed in eq. (3.11).

For wavy non-DLC ME tape, application of the foregoing analysis is complicated due to removal of lubricant from the tape and unstable head output in pause mode as shown in Fig. 3.1. Wear coefficient in pause mode for wavy non-DLC ME tape depends on the time chosen to evaluate head output (physical spacing between the head and tape surfaces), whereas, for MP tape there was no such problem because head output increased gradually throughout the experiment. Wear coefficient will be evaluated for wavy non-DLC ME tape in pause mode up to the time corresponding to lubricant depletion from areas of the tape that were contacting the head surfaces which occurred at about 80 s. Wear coefficient in streaming mode for ME tape will be evaluated over the first 200
play/rewind cycles during which an abrasive wear mechanism was operative. The result for ME tape is

\[(k_s)_{ME} > 4(k_p)_{ME} \]  

Abrasive effect observed in streaming mode with MP tape is also present in streaming mode for ME tape. Lubricant removal from the tape and transfer to the head surfaces for ME tape in pause mode as shown in Figs. 3.9 and 3.10 allowed a decrease in the physical spacing between the head and tape surfaces and lessened the disparity between wear coefficients in streaming and pause modes for ME tape as compared to MP tape.

Figure 3.14 shows 3-D AFM profiles and optical micrographs of MIG head surfaces after running against lapping tape for 20 s and wavy non-DLC ME and MP tapes for 3 days. Metal core recession is defined to be the height difference between the ferrite and metal core surfaces at their interface. A well-defined uniform metal core recession can be seen for heads run against lapping tape and wavy non-DLC ME tape and is shown schematically for the head run against ME tape. The presence of stain on the metal core for the head run against MP tape makes metal core recession somewhat less obvious in the 3-D profile. Metal core recession was obtained by taking several 2-D cross sections across the ferrite-to-metal core interface and then averaging values obtained from the cross sections. The presence of stain on the metal core for the head run against MP tape complicated the analyses in the sense that the experimenter had to be careful that the metal core itself, and not the stain on the metal core, was used as the metal core level.

Metal core recession obtained with lapping, wavy non-DLC ME and MP tapes are 15, 25 and 12 nm, respectively. Thus, wavy non-DLC ME tape produced metal core recession about twice that produced by the other tapes, which gave similar values. These values are less than those reported in a previous study which used the same tapes and a NOP to measure metal core recession of CoNbZr MIG heads (Tsuchiya and Bhushan, 1994). This is somewhat surprising since Vickers hardness of CoNbZr was reported to be 700 kg/mm² which is comparable or even higher than that of Sendust, and both heads use a core of single crystal Mn-Zn ferrite (Tsuchiya and Bhushan, 1995). The AFM correctly measured metal core recession, whereas, the NOP apparently did not do so. Thus, a reliable method of measuring metal core recession of MIG heads has been developed which is similar to that used to measure pole tip recession in thin-film heads in this dissertation.

Optical micrographs in Fig. 3.14 show that stains formed on the metal core and glass surfaces of the head run against MP tape, and that no stains formed on heads run against lapping and wavy non-DLC ME tapes. It was shown that stains formed on these
Figure 3.14. 3-D AFM profiles and optical micrographs of a MIG head surface after running against lapping tape for 20 seconds and ME and MP tapes for 3 days.
heads when run against BaFeO tape (Patton and Bhushan, 1998a). Stains are generally brown in color. Stains on the metal core run against MP tape are more prevalent towards the leading edge of the head, and their growth may nucleate at interfaces between dissimilar materials (see MP stain in Fig. 3.14). Stains form more easily at lower tensions and lower contact pressures, and the stain formation on the core run against MP tape in Fig. 3.14 suggest that contact pressure in the vicinity of the head gap was lower on the leading side of the head which is expected in a convergent channel type of bearing (Bowden and Tabor, 1950). This phenomenon has recently been observed by other researchers (Kim et al., 1996).

AFM imaging proved to be a valuable technique to determine stain morphology and thickness and yielded information that could not be obtained with an optical microscope. Stains are readily observed in the 3-D AFM profiles of Fig. 3.14 for the head run against MP tape. Surface morphologies of stains formed on the metal core and glass surfaces are different which may indicate that the mechanism of stain formation for the surfaces is different. Stains on the metal cores are smooth films with voids or pores, whereas, stains on the glass are rough films with many high asperities. Thickness of the stains was determined by taking several 2-D cross sections across the metal core, and then the height difference between the stain on the metal core and any exposed areas of the metal core was measured. Thickness of the stain was measured at several locations and averaged to obtain an average stain thickness. The average thickness of the stain on the metal core run against MP tape is about 15 nm.

Figure 3.15 shows head contours formed after running against lapping tape for 20 seconds and wavy non-DLC ME and MP tapes for 3 days. Generally, lateral head contours formed by wavy non-DLC ME tape had larger radii of curvature than those formed by MP tape which is most evident along the line segments EF and IJ in Fig. 3.15. For line segment AB, stains on the head run against MP tape make interpretation of the data difficult. Based on tape stiffness data in Table 2.3, high TD stiffness of wavy non-DLC ME tape (compared to MP tape) caused lateral head contours formed by wavy non-DLC ME tape to have larger radii of curvature than those formed by MP tape.

Lateral head contours are symmetric with respect to the center of the head along line segment AB for heads run against all of the tapes. It was shown that head contours were symmetric along all line segments for heads run against a more compliant BaFeO tape (Patton and Bhushan, 1997a). Lapping, wavy non-DLC ME and MP tapes appear to have been twisted from the leading to trailing sides of the head in going over the head, since lateral contours for the heads run against these tapes along line segments EF
Figure 3.15. Schematic of a MIG video head with line segments illustrating locations on the head surface where the contour was measured with an AFM, and head contours formed after running against lapping tape for 20 seconds and ME and MP tapes for 3 days.
(leading side) and U (trailing side) are the mirror image of each other. High contact pressure is expected near the head gap on the trailing side of the head and transverse pressure profiles are influenced by hydrodynamic air film formation above the rotating upper drum and the lack of such a film above the stationary lower drum. Pressure gradients should be larger on the stationary lower drum side which may make lateral head contours asymmetric with respect to the center of the head because local head wear should increase at higher pressure. Lateral head contours along line segment U for heads run against lapping, wavy non-DLC ME and MP tapes have higher gradients on the stationary lower drum side than on the rotating upper drum side due to larger pressure gradients on the stationary lower drum side. The surprising results of symmetric gradients for line segment AB and higher gradients on the rotating upper drum side for line segment EF are probably due to tape rigidity and their inability to deform and uniformly contact the rotary heads. The amount of asymmetry in lateral head contours is more for wavy non-DLC ME tape than for MP tape. Table 2.3 shows that wavy non-DLC ME tape is stiffer than MP tape.

Longitudinal head contours formed by MP tape had smaller radii of curvature than those formed by wavy non-DLC ME tape as shown in line segments CD, GH and KL in Fig. 3.15. The lower stiffness of MP tape compared to wavy non-DLC ME tape may be responsible for this behavior.

3.2.3 Summary

Durability and magnetic reliability of MP tape was superior to that of ME tapes with and without a DLC coating when operated in the streaming mode of a rotary head recorder. Tribological and magnetic performance of ME tape was affected by waviness of the ME tape surface and the presence of a DLC coating. Magnetic performance of MP tape improved to a saturated performance level as the tape was worn smooth. High asperities on the virgin tapes were severed off the tapes during the record pass, and those that remained on the tape surface increased friction force and tape wear by three body abrasion early on in play/rewind cycling tests. Lower friction and virtually no wear were observed later in cycling tests (except for flat non-DLC ME tape) when loose wear debris were no longer on the tape surface and the wear mechanism was adhesive. Wear coefficient in streaming mode was larger than that in pause mode due to no escape path for abrasive particles in the contact interface in streaming mode. Different tapes were
dissimilar in their tendencies to cause head stains and they formed different preferred head shapes due to varying mechanical properties.

Waviness of one kind of non-DLC ME tape led to poor high density recording performance due to spacing loss as compared to flat ME and MP tapes. Both surface waviness and DLC coating increased spacing between the recording head and magnetic layer of a tape which decreased head output. For non-DLC ME tapes, waviness improved wear life from 350 to about 800 play/rewind cycles by preventing abrasive wear (loose wear debris could escape contact areas by settling into valleys on the tape surface), high friction and rapid reduction in head-to-tape spacing or intimate contact and subsequent early tape failure observed with flat ME tape (loose wear debris could not escape from contact areas). For flat ME tapes, DLC coating improved wear life only slightly. DLC coating prevented catastrophic abrasive wear, high friction and intimate contact observed with flat non-DLC ME tape, but the coating could not prevent lateral crack formation and subsequent interface instability. All of the ME tapes failed by catastrophic lateral crack formation driven by longitudinal tape tension or flexing of the tapes in the transport. For wavy non-DLC ME tape, localized damage areas initiated at high points or bumps on the tape surface were connected by lateral cracks across the tape width at tape failure, whereas, for flat ME tapes with and without a DLC coating no such localized wear occurred and lateral cracks generally propagated through coating defects at tape failure. In pause mode, DLC coating improved magnetic reliability and tribological performance of ME tape by preventing the head from contacting the metallic magnetic layer. This suggests that a tough DLC coating may lead to long life in streaming mode. Based on this study, a flat tape must be used for magnetic considerations and DLC coating is needed to prevent abrasive wear and intimate contact. Reducing the number of coating defects and optimization of the toughness of magnetic and DLC coatings are key parameters for future ME tapes.

3.3 Origins of Friction and Wear of the Thin Metallic Layer of ME Magnetic Tape

3.3.1 Friction Force and Head Output

Figure 3.16 shows friction force and head output during streaming and pause mode testing with ME tapes with 25 nm precoat particle size and precoat particle areal densities of 5, 10 and 60/µm². In streaming mode, friction force and head output were lower at a precoat particle areal density of 60/µm² than at smaller precoat particle areal
Figure 3.16. Friction force and head output during streaming mode and pause mode testing with ME tapes with a precoat particle size of 25 nm and precoat particle areal densities of 5, 10 and 60 particles/µm² (note dB level for streaming mode is with respect to the system noise level and 0 dB for pause mode is the initial playback rms voltage for each tape).
densities, which had similar friction force and head output. Lower head output for the tape with a precoat particle areal density of 60/μm² can be related to bearing ratio plots in Fig. 2.9. More bearing area closer to the highest point on the tape increases the distance from the magnetic head to the bulk of the magnetic coating. This decreases head output due to spacing loss. Pause mode performance of the tapes was similar, but at a precoat particle areal density of 60/μm², there were a few drops in head output that were not present at smaller particle areal densities.

Figure 3.17 shows friction force and head output during streaming mode testing with ME tapes with a precoat particle areal density of 60/μm² and precoat particle sizes of 12, 18 and 25 nm. Friction force decreased as precoat particle size increased, and the decrease is most pronounced in going from 12 to 18 nm particle size. Head output decreased as precoat particle size increased in streaming mode. At a precoat particle areal density of 60/μm², larger precoat particle size gives more bearing area close to the highest point on the tape as shown in Fig. 2.9. This increases the distance between the magnetic head and the bulk magnetic coating and gives lower head output due to spacing loss. At a precoat particle size of 12 nm, head output was highest but unsteady, and three drops in head output of about 5 dB with durations on the order of tens of seconds are seen in Fig. 3.17. Careful inspection of friction data for the 12 nm precoat particle size shows that friction force increased by about 0.5 mN during drops in head output. Based on the Wallace equation, loose wear debris particles between the head and tape surfaces increased head-to-tape spacing by about 80 nm and increased friction force due to ploughing. Relatively steady head output at precoat particle sizes of 18 and 25 nm suggests that the wear mechanism that created large drops in head output at a 12 nm precoat particle size is not present at larger precoat particle sizes.

Figure 3.17 shows friction force and head output during pause mode testing with ME tapes with a precoat particle areal density of 60/μm² and precoat particle sizes of 12, 18 and 25 nm. Friction force generally increased with time over the duration of pause mode experiments for each precoat particle size, and the rate of increase decreased with increased precoat particle size. Increase in friction force in pause mode with particulate tapes was explained in terms of plastic flow of the polymer binder (Osaki et. al., 1992). Plastic flow of sub-μm sized asperities on the ME tape surface is possible due to the large number of head passes experienced by the tape asperities in pause mode, which could increase friction force with time. Loose wear debris particles in the contact interface would also contribute a ploughing contribution to the friction force which could also increase friction with time. Head output generally increased with time in pause mode due
Figure 3.17. Friction force and head output during streaming mode and pause mode testing with ME tapes with a precoat areal density of 60/\(\mu\)m\(^2\) and precoat particle sizes of 12, 18 and 25 nm (note dB level for streaming mode is with respect to the system noise level and 0 dB for pause mode is the initial playback rms voltage for each tape).
to removal of lubricant from the tape surface as well as burnishing of the tape surface. For a precoat particle size of 12 nm, head output fell sharply after about 100 s and the further decreased and became unstable (friction force also became unsteady). Loose solid wear debris in the contact interface caused unstable head output and spacing loss and also contributed to high friction force. Head output had greater stability for 18 and 25 nm precoat particle sizes which suggests that less loose wear debris particles were generated for these tapes.

Figure 3.18 shows friction force and head output during streaming and pause mode testing with ME tapes with relative lubricant thicknesses of 1.0, 1.4 and 1.9. In streaming mode, friction force decreased with increased lubricant thickness. This is due to more lubricant being available at contact junctions between the head and tape surfaces which reduced adhesive shear strength of the contact junctions. Head output in streaming mode at a relative lubricant thickness of 1.9 was about 1 dB less than that at relative lubricant thicknesses of 1.0 and 1.4. In pause mode, initial behavior of head output depended strongly on relative lubricant thickness. As relative lubricant thickness increased, initial increase in head output was larger and smoother due to removal of a thicker lubricant film. Based on the Wallace equation and an initial increase in head output of about 0.7 dB over the first 200 seconds, lubricant thickness is about 10 nm for the tape with relative lubricant thickness of 1.9. Similarly, lubricant thickness is about 3 nm for the tape with relative lubricant thickness of 1.4 based on lubricant removal over the first 80 seconds. There is no clear lubricant removal regime for the tape with relative lubricant thickness of 1.0.

Figure 3.19 gives a summary of the effects of precoat particle areal density and size as well as relative lubricant thickness on tape performance during streaming mode operation with ME tapes. At a precoat particle size of 25 nm, friction force and head output at a precoat particle areal density of 60/µm² are less than that at smaller particle densities, which have similar values of friction force and head output. At a precoat particle density of 60/µm², increased particle size reduced both friction force and head output. For various relative lubricant thickness, friction force decreased with increased relative lubricant thickness. Head output at relative lubricant thickness of 1.9 was about 1 dB lower than that at smaller relative lubricant thicknesses.
Figure 3.18. Friction force and head output during streaming mode and pause mode testing with ME tapes with relative lubricant thickness of 1.0, 1.4 and 1.9 (note dB level for streaming mode is with respect to the system noise level and 0 dB for pause mode is the initial playback rms voltage for each tape).
Figure 3.19. Summary of the effects of precoat particle size and areal density, and relative lubricant thickness on friction force and head output during streaming mode operation with ME tapes.
3.3.2 Dropout Frequency and Interface Stability

Figure 3.20 shows the effect of precoat particle areal density and size, and relative lubricant thickness on dropout frequency in two dropout classes for ME tapes. At a precoat particle size of 25 nm, dropout frequency was somewhat insensitive to precoat particle areal density. For precoat particle areal densities of 5 and 10/μm², which exhibited similar friction force, dropout frequency was the same at each precoat particle areal density for both classes of dropouts. This suggests that the number of loose wear debris particles in the head-to-tape contact interface was the same in each case. Plastic deformation of high asperities occurred at precoat particle areal densities of 5 and 10/μm², and hence, plastic deformation is not necessarily associated with the production of loose wear debris particles. At a precoat particle size of 25 nm and areal density of 60/μm², which had elastic deformation of high contacting asperities, dropout frequencies were larger than those at 5 and 10/μm² areal densities due to brittle fracture of asperities which created loose wear debris particles in the head-to-tape contact interface. At a precoat particle areal density of 60/μm², dropout frequency generally decreased with increased precoat particle size. Dropout frequency for a 12 nm precoat particle size is at least an order of magnitude larger than for 18 and 25 nm precoat particle sizes. Brittle fracture or cohesive material failure of high isolated asperities due to shear stress brought on by friction force increased the number of loose wear debris particles in the head-to-tape contact interface. At various relative lubricant thickness, dropout frequency increased slightly in going from 1.0 to 1.4, and then decreased in going from 1.4 to 1.9. Larger dropouts (6-9 dB, 20-50 μs) caused by larger loose wear debris particles improved more in going from 1.4 to 1.9 than smaller dropouts. This suggests that a benefit of a thicker lubricant film is to reduce the number of large loose wear debris particles in the head-to-tape contact interface.

3.3.3 Tape Wear

Figure 3.21 shows bearing ratio plots from an AFM of virgin and used ME tapes with various precoat particle size and areal density at a 10 × 10 μm scan size. Bearing ratio plots for tapes with extreme values of precoat particle size and areal density are shown in Fig. 3.21. Contact between the head and tape surfaces occurs at high areas on the tape topography. If tape wear occurs, changes in bearing ratio curves are expected at small distances from the highest point on a tape. This is particularly true for the mild
Figure 3.20. Dropout frequency for ME tapes in 4-6 dB, 3-10 μs and 6-9 dB, 20-50 μs classes of dropouts for (a) a precoat particle size of 25 nm and precoat particle areal densities of 5, 10 and 60 particles/μm², (b) a precoat particle areal density of 60/μm² and overcoat particle sizes of 12, 18 and 25 nm and (c) relative lubricant thickness of 1.0, 1.4 and 1.9.
Figure 3.21. Bearing ratio plots from an AFM for virgin and used ME tapes with various precoat particle size and areal density at a scan size of $10 \times 10 \, \mu\text{m}$.
wear expected in these experiments. If tape wear occurs during use at high areas on the
tape either by brittle fracture of high tape asperities or by plastic flow of high tape
asperities to lower locations, the net effect should be to shift the used bearing ratio curve
to the left of the virgin curve for a given tape. For both the 25 nm, 5/μm² and 12 nm, 60/
μm² tapes, bearing ratio curves for the used tapes are shifted by about 20 nm to the left of
those of the virgin tapes, whereas, used bearing ratio curves for 25 nm, 60/μm² tape is
essentially unchanged as compared to the virgin tape. The 25 nm, 5/μm² and 12 nm,
60/μm² tapes were worn during use, and the 25 nm, 60/μm² did not wear with use. Thus,
the surface topography determines whether wear occurs for the tapes.

Figure 3.22 shows rms surface height, surface skewness and surface kurtosis for
virgin and used tape samples. Rms surface height was insensitive to tape use for all of the
tape samples. Both skewness and kurtosis decreased upon running the tape for all of the
tape samples. This is consistent with either removal of high tape asperities from the
surface or plastic flow of material in high tape asperities to lower locations, both of which
are synonymous with wear of the surface. Skewness and kurtosis changed the least for the
tape with precoat particle size of 25 nm and areal density of 60/μm². Thus, the tape with
precoat particle size of 25 nm and areal density of 60/μm² is more wear resistant than the
other tapes. Comparing skewness and kurtosis values for virgin tapes in Fig. 3.22, it is
seen that the 25 nm, 60/μm² tape has lower skewness and kurtosis than the other tapes.
Low skewness and kurtosis are desirable for near zero wear during sliding based on these
experimental results.

Figure 3.23 shows schematic illustrations of proposed wear mechanisms for tapes
exhibiting plastic deformation (25 nm, 5/μm²), elastic deformation (25 nm, 60/μm²) and
brittle fracture (12 nm, 60/μm²). The 2-D profiles of the virgin tape surfaces are not
schematic and are actual data from AFM profiles in Fig. 2.7. 2-D profiles of the tapes
sliding against the head were modified at contacting asperities to illustrate the effects of
plastic deformation and brittle fracture. The main difference between tapes that exhibit
plastic and elastic deformation is that there are more high asperities that contact the head
and help support the external load for tapes that undergo elastic deformation. Spreading
the load over more asperities reduces the normal force on a given asperity which in turn
reduces the strain of a given asperity. Each of d₁ and d₂ in Fig. 3.22 represent the distance
from the highest point on a virgin tape surface to the level of the head as it slides over
each tape for tapes that exhibit plastic and elastic deformation, respectively.

The fact that bearing ratio (see Fig. 3.21), skewness and kurtosis (see Fig. 3.22)
all changed for the tapes that plastically deformed indicates that high asperities underwent
Figure 3.22. Effect of tape use on rms surface height, surface skewness and surface kurtosis for ME tapes with various precoat particle size and areal density.

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Figure 3.23. Schematic illustrations of the effect of surface texture on head-to-tape contact condition and tape wear for tapes exhibiting plastic deformation, elastic deformation and brittle fracture. The recording head slides across the tape surface at velocity v. $F_{fp}$, $F_{fe}$ and $F_{fbf}$ represent friction force on the head in the cases of plastic deformation, elastic deformation and brittle fracture, respectively.
large irreversible strains. It is shown schematically in Fig. 3.23 that $d_1 > d_2$. This means that the highest asperities on the tapes which exhibited plastic deformation have been subjected to large strains or deformations. High strain has been associated with plastic deformation (Greenwood, 1967). In particular, a compliance parameter $w_p$ was defined which is essentially the allowed strain of an asperity before the onset of plastic deformation. The equation for compliance is

$$w_p = \beta \left( \frac{H}{E'} \right)^2$$  (3.13)

where $w_p$ is the compliance, $\beta$ is the radius of curvature of a spherical tape asperity, $H$ is the hardness of the tape and $E'$ is the composite modulus of Mn-Zn ferrite and the CoNi film (Greenwood, 1967). The compliance $w_p$ was calculated for a tape asperity with $\beta = 200$ nm, $H = 7$ GPa and $E' = 80$ GPa, where the elastic modulus of the ferrite and tape are taken to be 122 and 190 GPa, respectively (Bhushan, 1996). The compliance is $w_p = 1.5$ nm which is a typical compliance value for asperities on the tapes used in this study.

Bearing ratio was shifted about 20 nm ($> w_p$) to the left in Fig. 3.21 for a tape that exhibited plastic deformation (25 nm, 5/\mu m^2). However, the tape that exhibited elastic deformation (25 nm, 60/\mu m^2) had a much smaller shift in bearing ratio in Fig. 3.21. Thus, tapes that exhibited plastic deformation have high asperities that have been strained more than the typical compliance.

For tapes that exhibit brittle fracture, high isolated asperities are present on an otherwise smooth surface. Brittle fracture occurs because a given isolated asperity must withstand a large shear force. In order for the asperity to remain attached to the tape surface, cohesive forces must be strong enough such that the shear force needed to counter the force applied on the asperity by the head results in a shear stress on the asperity which is less than that required for brittle fracture. The major difference between tapes that exhibit plastic deformation and those that exhibit brittle fracture is that there are more asperity contacts for the tapes that exhibit plastic deformation which reduces shear stress on the asperities to a value less than that required for brittle fracture.

### 3.3.4 Analyses of Friction Mechanisms

Some analyses was conducted to determine if the energy required to plastically deform asperities on a tape that exhibited plastic deformation (for instance the tape with 25 nm precoat particle size and 5/\mu m^2 precoat particle areal density) could be correlated to the experimentally measured increase in friction force. The work to plastically deform the asperities is
where $W_p$ is the work done, $p$ is the pressure and $V$ is the volume. The intention here is an order of magnitude calculation. In eq. (3.14), $p$ will be taken to be equal to the hardness of the tape, and an estimate of $V$ for the tape can be obtained from Fig. 3.21. $p$ will be taken as 7 GPa which is a typical hardness value for a cobalt based metal alloy (Bhushan, 1996). For the 25 nm, 5/μm² tape, which exhibited plastic deformation, the bearing ratio curve for the worn tape is shifted to the left by about 20 nm from the virgin tape. Bearing ratio for the virgin tape at 20 nm from the highest point is about 0.01. For a $10 \times 10 \mu m$ scan size, this gives a bearing area of $1 \times 10^{-12} \ m^2$. To get an upper bound on $V$, it will be assumed that the bearing area is $1 \times 10^{-12} \ m^2$ from 20 nm below the highest point on the tape up to the highest point on the tape (an over estimate of $V$ as it is seen in Fig. 3.21 that bearing ratio for the virgin tape increases over the first 20 nm). This essentially treats the asperities as cylinders from 20 nm below the highest point on the tape to the highest point on the tape. The volume of the cylinders is

$$V = A l$$

where $V$ is the volume, $A$ is the cross sectional area and $l$ is the length. Taking $A = 1 \times 10^{-12} \ m^2$ and $l = 20 \ nm$ in eq. (3.15) to obtain $V$, and placing $V$ in eq. (3.14) gives $W_p = 1 \times 10^{-10} \ J$. This is an upper bound on the work or energy needed to plastically deform the asperities in a $10 \times 10 \mu m$ area of the tape.

The average power consumption in the plastic deformation process can be expressed as

$$P_{ave} = W_p/\Delta t = F_d v$$

where $P_{ave}$ is the average power consumption, $\Delta t$ is the time required for the head to sweep out 100 μm² of tape area, $F_d$ is the friction force associated with the plastic deformation and $v$ is the head-to-tape relative velocity. Using the fact that the head width is 60 μm, the distance that the head must travel to sweep out 100 μm² of tape area is 1.7 μm. Since $v = 3.8 \ m/s$, then $\Delta t = (1.7 \mu m)/(3.8 \ m/s) = 0.45 \mu s$, and using $W_p$ and $\Delta t$ in eq. (3.16) gives $P_{ave} = 0.23 \ mW$. From eq. (3.16), $F_d$ is equal to 0.06 mN which is an upper bound on $F_d$. From Fig. 3.19, it is seen that the difference in friction between the 25 nm, 5/μm² and 25 nm, 60/μm² tapes is on the order of 1 mN. Thus, it is not possible for the observed plastic deformation of the 25 nm, 5/μm² tape to be singularly responsible for the increase in friction force. From Fig. 3.20, it is seen that dropout frequencies are similar for the 25 nm, 5/μm²; 25 nm, 10/μm²; and 25 nm, 60/μm² tapes. Thus, the number of loose wear debris particles in the head-to-tape contact interface is similar in each case. This means that differences in friction force between the tapes is not due to
plowing by loose wear debris particles. If differences in friction force are not due to plastic deformation of asperities or plowing by loose wear debris particles, it must be due to differences in the real area of contact.

Analyses were also conducted to determine if the energy of cohesion for a tape that exhibited brittle fracture could be correlated to the measured increase in friction force. The work required to brittle fracture an asperity at its base is

\[ W_{bf} = 2\gamma A_b \]  

where \( W_{bf} \) is the work done to brittle fracture an asperity, \( \gamma \) is the surface energy and \( A_b \) is the cross sectional area of the base of the asperity. Surface energy values for cobalt and nickel are 1.5 J/m\(^2\) and 1.7 J/m\(^2\), respectively (Rabinowicz, 1965). \( \gamma \) will be taken to be 2 J/m\(^2\) in these calculations. For the 12 nm, 60/\(\mu\)m\(^2\) tape, which exhibited brittle fracture of asperities, a typical diameter of the high isolated asperities is about 200 nm. Using this diameter to calculate \( A_b \), and 2 J/m\(^2\) as \( \gamma \) in eq. (3.17) gives \( W_{bf} = 1.3 \times 10^{-13} \) J.

From Fig. 2.7, the number of high isolated asperities in a 10 x 10 \(\mu\)m area for the 12 nm, 60/\(\mu\)m\(^2\) tape is about five. If it is assumed that all five asperities are brittle fractured (which is unlikely and will lead to an overestimation of the friction force), and 5\( W_{bf} \) is used in place of \( W_p \) with \( \Delta t = 0.45 \) \(\mu\)s in eq. (3.16), the result is \( P_{ave} = 1.4 \) \(\mu\)W and \( F_{bf} = 0.37 \) \(\mu\)N. \( F_{bf} \) is the friction force associated with brittle fracturing the asperities. From Fig. 3.19, it is seen that the difference in friction between the 12 nm, 60/\(\mu\)m\(^2\) and 25 nm, 60/\(\mu\)m\(^2\) tapes is on the order of 1 mN. Thus, it is not possible that the energy required to brittle fracture the asperities on the 12 nm, 60/\(\mu\)m\(^2\) tape is singularly responsible for the increase in friction force.

Another interesting analyses of brittle fracture at an asperity level was conducted for the 12 nm, 60/\(\mu\)m\(^2\) tape. From Fig. 3.19, friction force for this tape is about 8 mN. For about five contacts per 100 \(\mu\)m\(^2\) area of tape, the total number of contacts over the 800 \(\mu\)m x 60 \(\mu\)m = 4.8 x 10\(^4\) \(\mu\)m\(^2\) head-to-tape contact area will be (4.8 x 10\(^4\)/100) x 5 = 2400 contacts. Thus, the average friction force on an asperity will be (8 mN)/2400 = 3.3 \(\mu\)N. It is reasonable to assume that if an asperity brittle fractures, it will occur due to an interaction with a rotary head that occurs over the width of the asperity which is about 200 nm. This is essentially the assumption made by Archard in deriving his wear equation (Archard, 1953). Using \( W_{bf} \) in place of \( W_p \) and \( \Delta t = (200 \) nm)/(3.8 m/s) = 53 ns in eq. (3.16) gives \( P_{ave} = 2.5 \) \(\mu\)W and \( F_{bf} = 0.65 \) \(\mu\)N. If a given asperity is acted on by a friction force on the order of 0.65 \(\mu\)N, then brittle fracture is likely. This is less than, but on the same order of magnitude of, the average friction force on each asperity of 3.3 \(\mu\)N which was calculated above.
The analyses can be extended to the 18 nm, 60/μm² tape, which had lower friction force, lower dropout frequencies, less brittle fracture of asperities and less loose wear debris particles than the 12 nm, 60/μm² tape. From Fig. 2.7, the number of high isolated asperities is similar for the 12 and 18 nm, 60/μm² tapes. However, the average diameter of the high isolated asperities for the 18 nm, 60/μm² tape is about twice that for the 12 nm, 60/μm² tape. From eq. (3.17), the energy to brittle fracture an asperity is proportional to $A_b$ which is proportional to the square of the diameter. However, $P_{ave}$ and $F_{bf}$ will be proportional to the diameter, since $W_{bf}$ is divided by $Δt$ to obtain $P_{ave}$ and $F_{bf}$. Thus, $F_{bf}$ for the 18 nm, 60/μm² tape will be 1.3 μN, which is twice that of the 12 nm, 60/μm² tape. 1.3 μN is still less than the average friction force on an asperity of 2.9 μN, and some brittle fracture should occur. However, the increased energy required to brittle fracture the larger asperities reduced the propensity for brittle fracture to occur.

The preceding analyses of the effect of plastic deformation and brittle fracture on friction force indicates that the measured difference in friction force between tapes (on the order of mN) cannot be due to supplying energy to plastic deformation and brittle fracture. For the tapes that exhibited plastic deformation with no indication of brittle fracture, higher friction force must be due to higher real area of contact. For tapes that exhibited brittle fracture, higher friction force resulted from ploughing by loose wear debris particles in the head-to-tape contact interface.

### 3.3.5 Summary

The origins of friction and wear of the thin metallic layer of ME magnetic tapes were determined at an asperity level using a commercial VCR as a tape transport, magnetometer and tribometer. The VCR was instrumented to measure friction force between the rotary heads and tape, head-to-tape spacing to nanometer vertical resolution, and sub-μs duration signal dropouts caused by loose wear debris particles in the head-to-tape contact interface. ME tapes with various surface texture and the same lubricant thickness were studied, as well as tapes with various lubricant thickness and the same surface texture. To measure the very subtle origins of wear, tapes were recorded and then played back only one time, and surface topography was measured with an AFM to see if the tapes were worn. For fixed asperity size, increased asperity areal density or more asperities prevented the plastic deformation that was observed at low asperity areal densities. More asperities increases load bearing area near the highest point on the tape. This prevents high strain and associated plastic deformation of high asperities. Thus,
spreading the load over more asperities prevents plastic deformation. Tapes that exhibited plastic deformation had higher friction force than the tape that exhibited elastic deformation. A simple model was developed which suggests that high friction force is not due to the energy required to plastically deform the asperities, but arises from high real area of contact during sliding for the tapes that plastically deform. Tapes that plastically deform do not exhibit higher signal dropout frequencies, and this implies that plastic deformation is not associated with loose wear debris particle formation. For smooth tapes with high isolated asperities, brittle fracture or cohesive material failure of asperities due to shear stress brought on by friction force resulted in loose wear debris generation, high plowing component to friction force and interface instability. A thicker lubricant layer reduced friction force by reducing the shear strength of adhesive contact junctions.
CHAPTER 4

ENVIRONMENTAL EFFECTS

Temperature and humidity of the environment in which a sliding interface is located are known to affect the friction and wear of the interface. Due to complexity of friction and wear phenomena, various trends are observed as the environment is changed depending on the sliding materials, type of lubricant and other factors. Using the power of the rotary head tape drive experimental system, relevant friction and wear mechanisms are studied by placing the tape drive in an environmental chamber and running experiments at various temperature and humidity.

4.1 Background

The effects of temperature and SH on the performance of ME and MP tapes must be understood to ensure that the tapes can operate satisfactorily in the operating envelope for a given application. Previous pause mode studies showed that ME tape performance improved when operated above a threshold humidity for a given temperature (with a threshold value that increased with temperature) due to condensed water which acted as an additional lubricant, and that MP tape performance was relatively insensitive to the environment (Tsuchiya and Bhushan, 1994). Capillary condensation of water menisci may occur around contact spots between the head and tape surfaces. Friction and wear mechanisms for ME and MP tapes in streaming mode are different from those in pause mode, and head-to-tape interface performance in streaming mode changes as the tapes are worn as shown in Chapter 3 of this dissertation. The effects of SH and temperature on streaming mode performance of the tapes is not known and needs to be understood to determine the optimum operating environment for each tape and to identify relevant friction and wear mechanisms which could lead to further improvement of the tapes.
Water films adsorbed onto surfaces from the atmosphere are expected to affect interface tribology. Both temperature and SH affect adsorption of water vapor onto surfaces. Adsorption generally increases with increasing SH at a given temperature (Lenher, 1925; Bowden and Throssel, 1951; Tadros et al., 1974; Liu and Mee, 1983; Tian and Matsudaira, 1993; Bhushan and Zhao, 1997). Lower adsorption has been measured as the temperature is increased at a given SH (Lenher, 1925; Bowden and Throssel, 1951). Thickness of adsorbed layers on a surface depends on the material, and significant adsorption may occur at low to moderate SH or only close to saturation (Lenher, 1925; Bowden and Throssel, 1951; Tadros et al., 1974; Liu and Mee, 1983; Bhushan and Dugger, 1990; Tian and Matsudaira, 1993; Bhushan and Zhao, 1997). It has been suggested that adsorption above one or two molecular layers is due to contamination on the surface which may explain the widely varying results reported in the literature (Bowden and Throssel, 1951).

High adhesion between solid surfaces has been associated with the presence of liquid surface films. High adhesion between solid surfaces with condensed water or other liquid films has been measured in earlier studies (Budgett, 1912; Stone, 1930; McFarlane and Tabor, 1950b; Bhushan and Dugger, 1990). Moisture in the contact zone between surfaces was found to persist when the surfaces were placed in a dry environment or heated which clearly demonstrates difficulty in removing condensed water vapor from between surfaces (Stone, 1930). Adhesion due to surface tension effects was found to correlate well with adsorbed water film thickness and decreased with increased surface roughness (McFarlane and Tabor, 1950b; Bhushan and Dugger, 1990). High static friction or stiction between solid surfaces has been associated with the presence of liquid surface films. High stiction between solid surfaces has been measured in earlier studies (Liu and Mee, 1983; Tian and Matsudaira, 1993; Gao and Bhushan, 1995; Bhushan and Zhao, 1997).

Capillary condensation of water vapor onto a surface may occur in an unsaturated environment according to the Kelvin equation (Adamson, 1982; Israelachvili, 1992). Validity of the Kelvin equation has been verified between crossed mica cylinders for meniscus radius of curvature as low as 4 nm (Fisher and Israelachvili, 1979; Fisher and Israelachvili, 1981). Spontaneous formation of water bridges between mica surfaces from undersaturated nonpolar liquids at a critical separation has been observed with an accompanying attractive force and high adhesion (Christenson, 1985; Christenson and Blom, 1987). In at least two cases it has been pointed out that the critical separation for meniscus water bridge formation should be related to Kelvin radius (Christenson et al., 1987).
1982; Christenson and Blom, 1987) In similar experiments in undersaturated vapor environments with liquid hydrocarbons and water, it was found that equations of bulk thermodynamics were valid for menisci radii 0.5 to 1.0 nm and higher for liquid hydrocarbons and 5 nm and higher for water (Fisher and Israelachvili, 1980). It was suggested that surface tension of water does not reach its full value for menisci near molecular dimensions (Fisher and Israelachvili, 1980).

The objective of this investigation was to study friction and lubrication mechanisms of the tapes during pause mode and streaming mode operation in various environments and their interplay with magnetic performance of the tapes. A model of the effect of capillary condensation on interface forces and stability and head-to-tape spacing in a sliding contact was developed to explain experimental data.

4.2 Model of Capillary Condensation in a Sliding Contact

The model proposed here concerns spontaneous water menisci formation between two contacting solids (magnetic head and tape) in relative motion. Generally, the head will be modeled as a rigid flat surface and the tape as a deformable rough surface. The basis of the model will be Kelvin's equation (Adamson, 1982; Israelachvili, 1992). For a pure incompressible liquid in equilibrium with its vapor which is assumed to be a perfect dilute gas, Kelvin's equation for capillary condensation is

$$r_K = -\frac{\gamma V}{RT \ln (p/p_s)}$$  \hspace{1cm} (4.1)

where $p$ is the pressure over the curved water surface of mean Kelvin radius $r_K$, $p_s$ is the saturation pressure at temperature $T$, $\gamma$ is the surface tension of the liquid against its vapor, $V$ is the molar volume of the liquid and $R = 8.31 \text{ J/(mole °K)}$ is the gas constant. Note that RH in fraction is $p/p_s$. Equation (4.1) predicts that liquid may be in equilibrium with its vapor at a pressure $p$ which is less than the saturation pressure $p_s$ if the surface of the liquid is curved with mean Kelvin radius $r_K$. The mean Kelvin radius $r_K$ is defined to be

$$\frac{1}{r_K} = \frac{1}{r_1} + \frac{1}{r_2}$$  \hspace{1cm} (4.2)

which can be written as

$$r_K = \frac{r_1}{1 + r_1/r_2}$$  \hspace{1cm} (4.3)

where $r_1$ and $r_2$ are meniscus radii of curvature along two mutually orthogonal planes.

Mean Kelvin radii calculated from eq. (4.1) for the six experimental conditions used in this study are given in Table 4.1. For these calculations at 22 and 32.2 °C and various RH, values of $\gamma$ and $V$ used are: $\gamma_{22} = 72.75 \text{ mN/m}$, $\gamma_{32.2} = 71.18 \text{ mN/m}$, $V_{22} = 105$
18.04 cm³/mole and V₃₂.₂ = 18.09 cm³/mole (Lide and Frederikse, 1994). At constant temperature, rₓ increases with increasing SH. At constant SH, rₓ decreases with increasing temperature. Kelvin radii are on the order of nanometers for the various experimental conditions.

<table>
<thead>
<tr>
<th>SH = 0.003</th>
<th>SH = 0.009</th>
<th>SH = 0.013</th>
<th>SH = 0.021</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 °C</td>
<td>0.35 nm</td>
<td>0.8 nm</td>
<td>2.4 nm</td>
</tr>
<tr>
<td>32.2 °C</td>
<td>0.25 nm</td>
<td>0.6 nm</td>
<td>1.3 nm</td>
</tr>
</tbody>
</table>

Table 4.1. Mean Kelvin radii rₓ calculated from the Kelvin equation for various environmental conditions used in this study.

To illustrate the concept of capillary condensation, consider the case of a spherical deformable wear debris particle sandwiched between two rigid flat surfaces under load W as shown in Fig. 4.1. From eq. (4.1), any capillary condensed water menisci must have rₓ > 0 since p < pₑ. For an arbitrarily curved meniscus surface, radii that lie on the side of a meniscus having greater pressure or the side from which the meniscus appears to be concave such as r₁ in Fig. 4.1 are positive, and radii that lie on the side of a meniscus having lower pressure or the side from which the meniscus appears to be convex such as r₂ in Fig. 4.1 are negative (Adamson, 1982). Thus, capillary condensation may occur as long as r₁ < |r₂|. Considering two limiting cases, if |r₂| >> r₁, then rₓ ~ r₁, and if |r₂| ~ r₁, then for finite rₓ, r₁ must be infinitesimally small which is readily seen for both cases from eq. (4.3). Thus, larger menisci can form if |r₂| >> r₁, and if |r₂| ~ r₁, menisci will be vanishingly small. This implies that the geometry of a deformed wear debris particle or asperity may, under some circumstances, determine whether capillary condensation will occur and that all menisci will be asymmetrical with |r₂| > r₁. Meniscus height h, contact radius a and particle radius b are defined in Fig. 4.1.

If capillary condensation occurs as shown in Fig. 4.1, there will be a meniscus force Fₓ acting on each flat surface tending to pull the surfaces together and deform the wear debris particle. Generally, meniscus force consists of the sum of a Laplace force, a
Figure 4.1. Schematic illustration of capillary condensation between a spherical deformable wear debris particle and two rigid flat surfaces as governed by the Kelvin equation. Note that $r_1$ rotates in the plane of the paper and $r_2$ rotates in an orthogonal plane.
surface tension force and a negligible buoyant force (Gao et al., 1991). The total meniscus force can be written as

\[ F_M = F_L + F_T \]  \hspace{1cm} (4.4)

where \( F_L \) is the Laplace force and \( F_T \) is the surface tension force. The Laplace force is due to the pressure difference across a curved meniscus. The Young and Laplace equation for the pressure difference across a curved meniscus is

\[ \Delta p = \frac{\gamma}{r_K} \]  \hspace{1cm} (4.5)

where \( \Delta p \) is the pressure difference across the meniscus and \( p_l \) is the pressure inside the liquid (Adamson, 1982; Israelachvili, 1992). Laplace force due to the pressure difference for the situation in Fig. 4.1 can be written as

\[ F_L = \Delta p \pi (r_2^2 - a^2) = \left( \frac{\gamma}{r_K} \right) \pi (r_2^2 - a^2). \]  \hspace{1cm} (4.6)

Surface tension force is due to direct contact of a meniscus surface with the flat and wear debris particle surfaces as shown in Fig. 4.1. By symmetry, only the normal component of the surface tension force is non-zero and can be written as

\[ F_T = 2\pi by \sin \phi \sin (\phi + \theta) \]  \hspace{1cm} (4.7)

where \( \phi \) and \( \theta \) (contact angle) are defined in Fig. 4.1. Combining eqs. (4.6) and (4.7) gives

\[ F_M = (\gamma/r_K)\pi (r_2^2 - a^2) + 2\pi by \sin \phi \sin (\phi + \theta). \]  \hspace{1cm} (4.8)

The surface tension contribution to the normal force has often been neglected by going to the limit of small \( \phi \) or other reasons (Gao et al., 1991; Israelachvili, 1992). The model being developed here does not assume that lateral dimensions of the contact zone are orders of magnitude larger than typical vertical dimensions such as surface roughness. Considering that sizable meniscus will be asymmetric with \( |r_2| > r_1 \), the small \( \phi \) limit does not exist for nanometer size contact spots and wear debris particles relevant to the smooth tapes used in this study. Thus, surface tension contribution to meniscus force may be significant for nanometer size contact spots and wear debris particles. Relevance of the model to earlier models which assume larger contact spots should be significant because poor lateral resolution of many measuring instruments and techniques fails to resolve high frequency components of surface roughness which may produce nanometer size contact spots.

Eqs. (4.1) - (4.8) have interesting implications as to how capillary condensed water menisci bridges can affect a sliding contact interface. They imply that the total meniscus force should depend on the partial pressure of water vapor \( p \), or equivalently, the SH of the atmosphere. Figure 4.2 illustrates how increasing SH affects interfacial forces in a sliding loaded contact between a deformable rough surface (magnetic tape)
and a rigid flat surface (magnetic head) under load $W$ at velocity $v$ with a coefficient of friction $\mu$. As $SH$ and Kelvin radius increase, more water bridges form between the surfaces which increases the total normal force $F_N$. For example in Fig. 4.2, the number of individual meniscus forces increases from two to four as $SH$ changes from low to high. As $F_N$ increases, it is expected that since the rough surface is deformable, that the separation of the surfaces will decrease. In the simplistic Hooke's law approximation that the normal force normal displacement relation is linear it can be written

$$F_N = k z \quad (4.9)$$

where $k$ is the spring constant for the interface and $z$ is the displacement of the mean line of the rough surface towards the flat surface. Equation (4.9) predicts that as $F_N$ increases the rough surface will move towards the smooth surface a distance governed by the interfacial stiffness $k$. The increase in $F_N$ will increase friction force $F_f$.

The analytical model predicts that the size of menisci formed between a debris particle and surfaces in a contact interface will be determined in part by eq. (4.1). In traversing the contact interface at velocity $v$ between a deformable rough surface and a rigid flat surface under load $W$, the situation in Fig. 4.3 will be encountered by a deformable wear debris particle. The extent of deformation of the particle will change according to the topography of the rough surface. It was pointed out earlier that larger menisci will be asymmetric with $|r_2| > r_1$. Deformation of the wear debris particle as illustrated in Figure 4.3 can cause capillary condensation of menisci around the particle by providing the asymmetric geometry needed for meniscus formation.

Various lubrication regimes are defined in Fig. 4.3 for a given particle size. In the dry lubrication regime, no menisci are formed around the particle independent of its state of deformation due to small mean Kelvin radius. In the meniscus regime, menisci are condensed around the particle with an accompanying meniscus force only when it is deformed in the interface. Consequently, a meniscus force on the rough surface is turned on and off according to the deformation of the particle, and the modulating force creates tape instability. In the partially flooded regime, menisci are condensed around the particle with an accompanying meniscus force independent of its state of deformation due to sufficiently large mean Kelvin radius. The meniscus force is maintained on the rough surface as the particle slides in the interface which creates no tape instability. In essence, the particle is encapsulated by menisci as it slides in the interface. In the fully flooded regime, menisci bridges are formed between the surfaces themselves due to mean Kelvin radius close to the summit-to-mean distance of the tape and severe tape instability may result.
Figure 4.2. Schematic illustration of the effect of increasing SH on capillary condensation and interfacial forces in a sliding loaded contact between a deformable rough surface and a rigid flat surface.
Figure 4.3. Schematic illustration of various lubrication regimes for a deformable wear debris particle sliding between a rigid flat surface and a deformable rough surface. SH represents specific humidity and DF represents dropout frequency.
Trends in experimental data will be explained using the proposed model. Measured quantities will be entered into the model. For instance, meniscus height can be determined at a given temperature and SH by noting when dropouts caused by a given size of particle enter the partially flooded regime. Meniscus height is twice the minimum value of $r_1$ that will allow meniscus bridge formation, and minimum RH in the contact interface can be calculated from eq. (4.1). The ability to directly measure friction force and to deduce changes in head-to-tape spacing and coefficient of friction allows us to calculate $k$ from eq. (4.9). Establishing a lower bound on RH in the contact interface and determining $k$ in a nanometer normal displacement regime has been accomplished for the first time in this dissertation. As long as the Hooke's law approximation is valid, $k$ is useful for predicting changes in head-to-tape spacing for a given change in normal force.

4.3 Wavy Non-DLC ME and MP Tapes

4.3.1 Pause Mode

Figure 4.4 shows friction force and head output during pause mode testing with wavy non-DLC ME and MP tapes in the same environment. ME tape lacked the stability in friction and head output exhibited by MP tape. Head output for wavy non-DLC ME tape shows a rapid increase to about +1 dB, implying a decrease in head-to-tape spacing of about 10 nm for a recorded wavelength of 0.6 μm based on the Wallace equation. Since the lubricant thickness is also 10 nm, this implies the removal of essentially all of the lubricant from the wavy non-DLC ME tape surface. After lubricant depletion, interaction of the rotary heads with the metallic layer prevented the rapid increase in head output observed during lubricant removal and generated solid tape debris, which, at this environmental condition, caused signal dropouts upon traversing the tape contact region of the head surface. The friction force increased as the lubricant was removed, and further increased and became unstable after lubricant depletion with friction spikes temporally correlated to signal dropouts.

Figure 4.5 shows relative durability results of pause mode experiments using wavy non-DLC ME tape at various temperatures and SHs. At constant temperature, increased SH improved tape performance. At constant SH, decreased temperature improved tape performance. At a given temperature, more water vapor improved performance, and the amount of water vapor needed for improved performance decreased at lower temperatures. Experiments performed at various SH on the RH = 80% line
Figure 4.4. Friction force and head output during pause mode testing with (a) wavy non-DLC ME tape and (b) MP tape in the same environment.
Figure 4.5. Comparative durability results of pause mode experiments using wavy non-DLC ME tape at various temperatures and specific humidities.
yielded good or excellent results in the operating temperature range of 15.6 to 32.2 °C. However, at temperatures lower than 15.6°C, ME tape performed satisfactorily at lower humidity to RH = 50%.

Figure 4.6 (a) shows friction force and head output at selected SH at constant temperature. At three different temperatures, increased SH improved performance of wavy non-DLC ME tape. Increased SH reduced the lubricant removal rate and improved signal stability after lubricant depletion. Capillary condensation of water menisci onto interface components acted as an additional replenished lubricant and a mediator for solid debris to smoothly traverse the contact region of the head and tape.

Figure 4.7 shows average lubricant removal rates during pause mode testing at various SH at constant temperature for wavy non-DLC ME tape at the six experimental conditions in Figure 4.6 (a). At each temperature, increasing the SH reduces the average lubricant removal rate. Generally, lower temperatures have lower average lubricant removal rates. Average lubricant removal rates are calculated over the first minute of pause mode testing from data such as that shown in Fig. 4.8, which shows head output versus time data at three environmental conditions.

Figure 4.6 (b) shows the friction force and head output data at selected temperature at constant SH. At three different values of SH, decreased temperature reduced the lubricant removal rate and improved signal stability after lubricant depletion. The average lubricant removal rate decreased from 10 to 4.3, 10 to 5 and 6.25 to 5 nm/min for SH equal to 0.009, 0.013 and 0.024, respectively, as the temperature was reduced in each case. Figure 4.9 shows a typical PFPE lubricant viscosity-temperature relation and average lubricant removal rates during pause mode testing at various temperatures at constant SH for wavy non-DLC ME tape. At each SH, reducing the temperature reduces the average lubricant removal rate. Generally, higher SHs have lower average lubricant removal rates. The Kelvin equation predicts that more capillary condensation of water menisci occurs at lower temperature allowing additional lubrication. The role of lubricant viscosity alone cannot be determined from these experiments.

Figure 4.10 shows the friction force and head output in different environments on the performance of MP tape. Figures 4.10 (a) and 4.10 (b) show that MP tape performance was insensitive to changes in temperature at constant SH, and both friction force and head output increased during each experiment due to mild burnishing of the tape surface. Figures 4.10 (b) and 4.10 (c) show that a thicker water film resided on the interface components at high SH, which was not present at lower SH at a temperature of
Figure 4.6. Friction force and head output during testing with wavy non-DLC ME tape at (a) various specific humidities at constant temperature and (b) various temperatures at constant specific humidity.
Figure 4.7. Average lubricant removal rates during pause mode testing at various specific humidities at constant temperature for wavy non-DLC ME tape.
Figure 4.8. Head output vs. time during pause mode testing illustrating lubricant removal from the wavy non-DLC ME tape surface at various temperatures and specific humidities.
Figure 4.9. Typical PFPE lubricant viscosity-temperature relation and average lubricant removal rates during pause mode testing at various temperatures at constant specific humidity for wavy non-DLC ME tape.
Figure 4.10. Friction force and head output during pause mode testing with MP tape at various temperatures and specific humidities.
32.2 °C. The rapid increase in head output in Fig. 4.10 (c) to 0.5 dB over the first 40 s of running suggests that about 2.5 nm of the water film on each interface component was removed by the friction force exerted on the components during this time. Subsequent head output decreased slightly as the water film was partially reestablished on the head and tape surfaces. Generally, based on experiments at conditions not shown in Fig. 4.10, Figs. 4.10 (a) and 4.10 (b) are most representative of MP tape behavior in various environments. No water film was found on MP tape at SHs below 0.024.

4.3.2 Streaming Mode

Figure 4.11 shows progression of head output in the initial stages of wear during play/rewind cycling with wavy non-DLC ME, and MP tapes. Head output was below 0 dB during the third play/rewind cycle for both ME and MP tapes and remained below 0 dB through 25 play/rewind cycles. Analyses of head and tape samples used in play/rewind cycling experiments suggest that wear debris on the tape surface increased head-to-tape spacing over the first few cycles. Thus, the interface condition significantly affects head output, and in the first few play/rewind cycles head output decreased as the tape was pushed away from the heads by wear debris on the tape surface. Changes in head output level can also be used to study the effect of environment on interface performance.

Figure 4.12 shows the effect of SH on head output for wavy non-DLC ME tape and MP tape at temperatures of 22 and 32.2 °C during the first play/rewind cycle under equilibrium conditions. At each temperature, head output for each tape was influenced by spacing loss incurred during both the record pass and first play/rewind cycle. Considering signal loss incurred during both the record pass and first play/rewind cycle, a 1 dB increase in head output corresponds to about a 6 nm reduction in head-to-tape spacing at a 0.6 µm recording wavelength. Since magnetization of the tapes and heads are decreasing functions of temperature, it is expected that the set of data at 32.2 °C will lie below the set of data at 22 °C in Fig. 4.12 (Mee, 1964; Bhushan, 1992). Curie temperatures for the magnetic film used for wavy non-DLC ME tape and magnetic particles in MP tape are both about 1000 °K, whereas, those for the Mn-Zn ferrite head core and Sendust metal alloy in the gap are about 420 °K and 770 °K, respectively. Low Curie temperature of Mn-Zn ferrite causes instability in head flux with respect to small temperature changes and is the most likely cause of the measured dependence of head output on temperature. Without explicitly knowing the magnetization versus temperature
Figure 4.11. Progression of head output in the initial stages of wear during play/rewind cycling with wavy non-DLC ME tape and MP tape (note 0 dB is the playback rms voltage during the first play/rewind cycle for each tape).
Figure 4.12. Effect of specific humidity on head output during the first play rewind cycle for wavy non-DLC ME tape and MP tape at temperatures of 22 °C and 32.2 °C. Note that the given specific humidity was maintained during both the record pass and the first play/rewind cycle (note 0 dB is the playback rms voltage at 22 °C and SH = 0.009 for each tape).
relations for the tapes and heads, it is not possible to separate the effects of temperature and interface performance on head output. Thus, we can only determine the effect of SH on head output at each temperature for the tapes, and we will not compare data taken at different temperatures. For both wavy non-DLC ME tape and MP tape, head output increased with increased SH at each temperature. High head output is associated with small spacing loss and thus high SH apparently allowed the tapes to intimately contact the heads. The additional normal force at high SH due to additional menisci bridges between the surfaces pulled the tape closer to the heads during both the record pass and first play/rewind cycle and reduced spacing loss.

Figure 4.13 shows real time response of head output and friction force to changes in RH for wavy non-DLC ME tape and MP tape at temperatures of 22 and 32.2 °C. In these non-equilibrium experiments, the first minute of the experiment was under equilibrium conditions at each temperature and 45% RH, and then RH was modulated in one cycle of a square wave before finally being held again for one minute at 45% RH. Head output level and friction force were monitored throughout each experiment.

Head output generally modulated in phase with RH for wavy non-DLC ME tape and MP tape. Thus, addition and removal of water vapor in real time, since it changed head output according to RH, shows that the amount of water vapor in the air and condensed on the interface components directly affected head-to-tape spacing and the tribological behavior of the interface. Head output for MP tape responded immediately to changes in RH, and at constant temperature head output was a simple function of RH. Head output for wavy non-DLC ME tape responded with no delay to increases in RH, but particularly at 32.2 °C, there was delayed or no response of head output to decreases in RH. For example, as shown in Fig. 4.13 for wavy non-DLC ME tape at 22 and 32.2 °C, head output decreased linearly from about 150 to 425 s, even though relative humidity was ramped down rapidly to about 10% RH from 60 to 200 s and held at about 10% RH from 200 to 425 s. Head output for wavy non-DLC ME tape at 32.2 °C remained constant during the final pull down of RH which began at about 700 s. Thus, for wavy non-DLC ME tape head output did not modulate exactly in phase with RH, and therefore was not a simple function of RH. This suggests that adsorbed water penetrated, displaced or chemically bonded to the lubricant because adsorbed water was not easily removed from the tape surface.

Friction force generally modulated in phase with RH for wavy non-DLC ME tape and MP tape. Addition and removal of water vapor in real time, since it changed friction force according to RH, shows that the amount of water vapor in the air and condensed on
Figure 4.13. Real time response of head output and friction force to non-equilibrium changes in relative humidity for wavy non-DLC ME tape and MP tape at temperatures of 22 °C and 32.2 °C during the first play/rewind cycle (note 0 dB is the initial playback rms voltage for each tape at each temperature and 45% RH).
the interface components directly affected the nature of the frictional contact. According to the model presented earlier, higher friction at higher RH or SH resulted from increased meniscus formation between contacting asperities on the head, tape and wear debris particle surfaces which increased normal and friction forces. Friction force for MP tape responded immediately to changes in RH, and at constant temperature friction force was a simple function of RH. Friction force for ME tape responded with no delay to increases in RH, but its response was delayed to decreases in RH. For example as shown in Fig. 4.13 for wavy non-DLC ME tape at 22 and 32.2 °C, friction force decreased linearly from about 150 to 425 s, even though humidity was ramped down rapidly to about 10% RH from 60 to 200 s and held at about 10% RH from 200 to 425 s. Friction force also showed hysteresis (particularly at 32.2 °C) in the sense that friction force did not return to its initial value (during the first minute of experiment) after the final pull down of RH which began at about 700 s. Thus, friction force did not modulate exactly in phase with RH for wavy non-DLC ME tape, and therefore was not a simple function of RH. This again suggests that adsorbed water penetrated, displaced or chemically bonded to the lubricant because adsorbed water was not easily removed from the tape surface.

It is interesting to note that variations of friction force and head output in Fig. 4.13 are similar for both tapes at both temperatures. Similarity of variations in friction force for both tapes suggests that contact angles with water and bearing ratio curves for the tapes should be similar. Macroscopic contact angle for water drops on the tapes are about 85° for both tapes. Bearing ratio curves are similar for wavy non-DLC ME tape and MP tape which suggests that available bearing area for coupling the tape and head surfaces via menisci is similar for the tapes. For similar variations in friction force, similarity of variations in head output suggests that the tapes have similar interfacial spring constants as defined by eq. (4.9). Varying RH from 20 to 80% in Fig. 4.13 increased friction force by about 1.5 mN and the head output by about 0.75 dB (about a 7.5 nm reduction in head-to-tape spacing). Since the coefficient of friction is about 0.4, normal force changed by about 3.75 mN. Using the given changes in normal force and head-to-tape spacing in eq. (4.9), the interfacial spring constant is about 0.5 mN/nm.

Figure 4.14 shows the effect of SH on dropout frequency in various classes of dropouts for wavy non-DLC ME tape and MP tape at a temperature of 22°C under equilibrium conditions. The tapes were in a dropout condition less than 10% of the time which illustrates the intermittent nature of the wear events which caused the dropouts. Dropout behavior of wavy non-DLC ME tape and MP tape at 22 °C was different for the two kinds of tapes as SH was varied in each case. Generally for a particular dropout class
at 22 °C, if increased SH improved wavy non-DLC ME tape performance, then MP tape performance degraded with increased SH. For example in Fig. 4.14, the 4-6 dB and 3-10 μs dropout class illustrates this behavior. Increasing SH from 0.003 to 0.013 reduced dropout frequency by nearly an order of magnitude for wavy non-DLC ME tape, whereas, for MP tape dropout frequency increased by nearly an order of magnitude with the same increase in SH. Thus, the effect of SH on tape performance depended on the kind of tape being used in the experiment.

For a given kind of tape, dropout behavior as SH was varied was not the same for all classes of dropouts. Classes of dropouts that show the same trend with changing SH are probably caused by wear debris particles of about the same size. Larger wear debris particles move the tape farther from the head gap than smaller wear debris (if located in the same proximity to the head gap) and generally cause dropouts of larger depth. However, wear debris of a given size caused dropouts of varying depth and duration which depended on the proximity of the particle to the head gap. The closer a given particle was to the head gap created a larger tent size for the tape over the head gap, and the particle was swept out of the interface quickly due to higher contact pressure near the head gap. For example in Fig. 4.14 for wavy non-DLC ME tape, all of the 4-6 dB, and the 6-9 dB, 0.5-3 and 3-10 μs dropouts showed the same behavior as SH was varied. This suggests that all of these dropout classes are caused by particles of about the same size (60-90 nm diameter by the Wallace equation), and that if a particle passes directly over the head gap and causes a large tape displacement and corresponding dropout, it is generally of shorter duration due to being swept quickly through the high contact pressure region. Based on the data in Fig. 4.14 and the Wallace equation, larger dropout classes are caused by particles with diameters larger than 90 nm. The fact that increasing SH affects interface stability differently, depending on the size of particle responsible for a given class of dropouts, is of interest.

The effect of SH on a given class of dropouts depends on the size of particle that causes those dropouts. For both wavy non-DLC ME tape and MP tape, there are distinct patterns in Fig. 4.14 for dropout frequencies as SH was changed from 0.003 to 0.009 and 0.009 to 0.013. Patterns for wavy non-DLC ME tape are: (1) decrease and decrease for all of 4-6 dB, and 6-9 dB, 0.5-3 and 3-10 μs; (2) increase and decrease for 6-9 dB, 10-20 μs and 9-12 and >12 dB, 0.5-3 and 3-10 μs and (3) decrease and increase for 9-12 and >12 dB, 10-20 and 20-50 μs, respectively. The first pattern for wavy non-DLC ME tape occurred with small dropouts which were likely caused by small wear debris particles, and similarly, the second and third patterns for wavy non-DLC ME tape were likely
Figure 4.14. Effect of specific humidity on dropout frequency in various classes of dropouts for wavy non-DLC ME tape and MP tape at a temperature of 22 °C during the first play/rewind cycle. Note that the given specific humidity was maintained during both the record pass and the first play/rewind cycle.
caused by medium and large size wear debris particles, respectively. For small size wear debris particles using wavy non-DLC ME tape at 22 °C, higher SH reduced dropout frequencies caused by the particles over a range of SH from 0.003 to 0.013. For medium size wear debris particles using wavy non-DLC ME tape at 22 °C, when SH was increased from 0.003 to 0.009, there was a mild increase in dropout frequencies caused by the particles. However, when SH was further increased to 0.013, there was a decrease in those dropout frequencies. For large size wear debris particles using wavy non-DLC ME tape at 22 °C, when SH was increased from 0.003 to 0.009, there was a mild decrease in dropout frequencies caused by the particles. However, when SH was further increased to 0.013, there was an increase in those dropout frequencies.

Patterns for MP tape in Fig. 4.14 are: (1) increase and increase for 4-6 dB, 0.5-3 and 3-10 μs and 6-9 dB, 0.5-3 and 3-10 μs and (2) decrease and increase for 4-6 dB, 20-50 μs; 6-9 dB, 10-20 and 20-50 μs and all of 9-12 and >12 dB, respectively. The first pattern for MP tape occurred with small dropouts which were likely caused by small wear debris particles, and the second pattern for MP tape was likely caused by medium and large wear debris particles. For small size wear debris particles using MP tape at 22 °C, higher SH increased dropout frequencies caused by the particles over a range of SH from 0.003 to 0.013. For medium and large size wear debris particles using MP tape at 22 °C, when SH was increased from 0.003 to 0.009, there was a decrease in dropout frequencies caused by the particles. However, when SH was further increased to 0.013, there was an increase in those dropout frequencies.

Data for wavy non-DLC ME tape and MP tape at 22 °C suggest that there are different regimes of dropout behavior according to the relative size difference between wear debris particles and spontaneously formed water menisci. Data for wavy non-DLC ME tape at 22 °C suggest that small particles caused fewer dropouts when SH was increased from 0.003 to 0.009 and from 0.009 to 0.013. Medium size wear debris particles caused fewer dropouts when SH was increased from 0.003 to 0.013, but they caused more dropouts when SH was increased from 0.003 to 0.009. Thus, medium size wear debris particles need more water vapor than small particles to improve performance, and they appear to have a regime in which additional water vapor caused more dropouts. Large size wear debris particles caused fewer dropouts when SH was increased from 0.003 to 0.009, but they caused more dropouts when SH was increased from 0.009 to 0.013.

Considering the relative size of particles and that Kelvin radius is larger at higher values of SH, data for wavy non-DLC ME tape confirm the existence of the first three
lubrication regimes proposed in Fig. 4.3. In the dry regime, increased SH reduced dropout frequencies due to better lubricity of the surfaces. Examples of the dry regime for wavy non-DLC ME tape in Fig. 4.14 are 9-12 and >12 dB, 10-20 and 20-50 μs from 0.003 to 0.009 SH. Increased SH increased dropout frequencies in the meniscus regime because larger mean Kelvin radius allowed menisci to form around a particle only when it was deformed in the interface. Condensation and subsequent evaporation of menisci around a debris particle during sliding resulted in the appearance and disappearance of menisci forces which caused tape instability. Examples of the meniscus regime for wavy non-DLC ME tape in Fig. 4.14 are: 6-9 dB, 10-20 μs from 0.003 to 0.009 SH; 9-12 and >12 dB, 0.5-3 and 3-10 μs from 0.003 to 0.009 SH and 9-12 and >12 dB, 10-20 and 20-50 μs from 0.009 to 0.013 SH. In the partially flooded regime, increased SH decreased dropout frequencies as larger mean Kelvin radius allowed more menisci to be maintained around wear debris particles independent of their state of deformation. Examples of the partially flooded regime for wavy non-DLC ME tape in Fig. 4.14 are: all of 4-6 dB from 0.003 to 0.013 SH; 6-9 dB, 0.5-3 and 3-10 μs from 0.003 to 0.013 SH; 6-9 dB, 10-20 and 20-50 μs from 0.009 to 0.013 SH and 9-12 and >12 dB, 0.5-3 and 3-10 μs from 0.009 to 0.013 SH.

MP tape at 22 °C shows only dry and meniscus regimes of dropout behavior over a range of SH from 0.003 to 0.013 as shown in Fig. 4.14. Examples of the dry regime for MP tape in Fig. 4.14 are: 4-6 dB, 20-50 μs from 0.003 to 0.009 SH; 6-9 dB, 10-20 and 20-50 μs from 0.003 to 0.009 SH and all of 9-12 and >12 dB from 0.003 to 0.009 SH. Any transition which varied SH within various dropout classes for MP tape not mentioned as being in the dry regime was in the meniscus regime. Most classes of dropouts for wavy non-DLC ME tape at 22 °C operated in the partially flooded regime, whereas, MP tape at 22 °C showed only dry and meniscus regimes associated with smaller menisci radii. The 5-10 nm of liquid lubricant on the wavy non-DLC ME tape surface apparently shifted the lubrication regimes towards those associated with larger menisci for a given class of dropouts.

Figure 4.15 shows the effect of SH on dropout frequency in various classes of dropouts for wavy non-DLC ME tape at 32.2 °C under equilibrium conditions. Wavy non-DLC ME tape at 32.2 °C shows meniscus and partially flooded regimes as well as the last lubrication regime proposed in Fig. 4.3 or the fully flooded lubrication regime. Examples of the meniscus regime for wavy non-DLC ME tape in Fig. 4.15 are 9-12 and >12 dB, 10-20 and 20-50 μs from 0.003 to 0.013 SH. Examples of the partially flooded regime for wavy non-DLC ME tape in Fig. 4.15 are all of 4-6 dB from 0.003 to 0.013 SH and 6-9 dB, 0.5-3 μs from 0.003 to 0.013 SH. All dropout classes for wavy non-DLC ME
Figure 4.15. Effect of specific humidity on dropout frequency in various classes of dropouts for wavy non-DLC ME tape and MP tape at a temperature of 32.2 °C during the first play/rewind cycle. Note that the given specific humidity was maintained during both the record pass and the first play/rewind cycle.
tape were in the fully flooded regime in going from a SH of 0.013 to 0.021 because there was a sharp increase in all dropout frequencies over this range of SH. Since the fully flooded regime was operative in all dropout classes independent of the sizes of the particles which caused the various tape instabilities, condensation of menisci between the surfaces themselves due to mean Kelvin radius on the order of the summit-to-mean distance of the tape is the likely cause. The largest increases in dropout frequency occurred for 6-9 dB, 3-10 and 10-20 ms and 9-12 and >12 dB, 0.5-3, 3-10 and 10-20 ms dropout classes. Wear debris particles of > 90 nm diameter are responsible for these dropout classes which would reach the partially flooded regime at a meniscus height of about 45 nm. A 45 nm meniscus height would imply menisci formation between the head surface and nearly all of the bearing area of ME tape. The 5-10 nm of liquid lubricant on the wavy non-DLC ME tape surface would reduce the meniscus height needed to couple the head and tape surfaces by 5-10 nm. This suggests that excitation of the above dropout classes is probably due to menisci formation between the head and tape surfaces.

The effect of SH on dropout frequency in various classes of dropouts for MP tape at 32.2 °C under equilibrium conditions is shown in Fig. 4.15. MP tape at 32.2 °C shows dry, meniscus and partially flooded regimes. Examples of the dry regime for MP tape in Fig. 4.15 are all of 9-12 and >12 dB from 0.003 to 0.013 SH. Examples of the meniscus regime for MP tape in Fig. 4.15 are: all of 4-6 dB from 0.003 to 0.013 SH; 6-9 dB, 0.5-3, 3-10 and 10-20 μs from 0.003 to 0.013 SH; 6-9 dB, 20-50 μs from 0.013 to 0.021 SH and all of 9-12 and >12 dB from 0.013 to 0.021 SH. Examples of the partially flooded regime in Fig. 4.15 are all of 4-6 dB from 0.013 to 0.021 SH and 6-9 dB, 0.5-3, 3-10 and 10-20 μs from 0.013 to 0.021 SH. The partially flooded regime was operative for MP tape only when SH was increased from 0.013 to 0.021.

Data in Figs. 4.14 and 4.15 can be used to determine heights of capillary condensed menisci around debris particles which caused the various tape instabilities. According to the model illustrated in Fig. 4.3, when the meniscus height is equal to the particle radius the particle is encapsulated by menisci and enters the partially flooded regime. Dropout classes used in this study are particularly sensitive to tape displacements caused by 60-90 nm and > 90 nm diameter particles. At each temperature, by noting the SH at which dropout classes caused by a given size of particle enter the partially flooded regime, meniscus height can be equated to the particle radius. Table 4.2 gives menisci heights for wavy non-DLC ME tape and MP tape at 22 and 32.2 °C deduced from Figs. 4.14 and 4.15. Meniscus height of wavy non-DLC ME tape is adjusted for 10 nm of liquid lubricant by subtracting 5 nm from the meniscus height deduced from Figs. 4.14
and 4.15 (assuming meniscus from debris particle to the tape couples to the lubricant surface). Menisci heights are similar for wavy non-DLC ME tape and MP tape at each temperature which further confirms the geometric nature of the capillary condensation mechanism. At each temperature, menisci heights generally increased with increased SH.

It should be noted that values in Table 4.2 are larger than Kelvin radii in Table 4.1. RH in the contact interface can be calculated using data in Table 4.2 and eq. (4.1). For a given meniscus height, the minimum value of \( r_1 \) which allows the meniscus bridge to form is

\[
r_{1\text{min}} = h/2
\]

(4.10)

Using \( r_K \sim r_{1\text{min}} \) in eq. (4.1) will give a lower bound on RH in the contact interface at a given condition. As an example consider wavy non-DLC ME tape at 22 °C and SH = 0.009 (RH = 45%). From Table 4.2, \( h \) is at least 25 nm which gives \( r_{1\text{min}} \) of 12.5 nm. Using \( r_K = 12.5 \text{ nm} \) in eq. (4.1) gives RH > 96% and SH > 0.0156 in the contact interface. Other conditions in Table 4.2 that have an established non-zero minimum value for \( h \) have even higher values of RH and SH in the contact interface. SH or equivalently partial pressure of water vapor in the contact interface are close to their saturation values. Proximity and intimate contact of the surfaces apparently increases the vapor pressure between the head and tape surfaces over that maintained in the environmental chamber.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>SH = 0.009</th>
<th>SH = 0.013</th>
<th>SH = 0.021</th>
</tr>
</thead>
<tbody>
<tr>
<td>wavy non-DLC ME(^a)</td>
<td>22 °C</td>
<td>25 nm &lt; ( h ) &lt; 40 nm</td>
<td>( h ) &gt; 40 nm</td>
</tr>
<tr>
<td>MP</td>
<td>22 °C</td>
<td>( h ) &lt; 30 nm</td>
<td>( h ) &lt; 30 nm</td>
</tr>
</tbody>
</table>

\(^{a}\) Value for wavy non-DLC ME tape is adjusted for 10 nm of liquid lubricant

Table 4.2. Menisci heights deduced from Figs. 4.14 and 4.15.
Figure 4.16 shows the effect of temperature on dropout frequency in various classes of dropouts for wavy non-DLC ME tape at a SH of 0.003 under equilibrium conditions. This is the smallest value of SH used in these experiments, and consequently, mean Kelvin radius was relatively small. Wavy non-DLC ME tape has 5-10 nm of liquid lubricant on the tape surface and lubricant properties are expected to significantly affect tape performance at small values of SH where menisci radii are expected to be small. Dropout frequency in every class of dropouts for wavy non-DLC ME tape at a SH of 0.003 decreased in going from 22 to 32.2 °C. Since increased temperature at a constant SH of 0.003 improved performance in all dropout classes independent of the particle sizes which caused the various tape instabilities, it was probably temperature dependence of lubricant properties that caused change in tape performance. Viscosity-temperature relations for perfluoropolyether lubricants show that kinematic viscosity decreases by about a factor of two with a 10 °C increase in temperature within the range of temperatures used in these experiments (Bhushan, 1996). Thus, increased lubricant mobility at 32.2 °C increased lubricity and reduced dropout frequencies. The 6-9 dB and 9-12 and >12 dB classes of dropouts improved more than the 4-6 dB classes of dropouts, and hence, dropouts caused by larger particles improved more than those caused by smaller particles.

The effect of temperature on dropout frequency in various classes of dropouts for MP tape at a SH of 0.003 under equilibrium conditions is shown in Fig. 4.16. Based on data for MP tape in Figs. 4.14 and 4.15, and the fact that menisci radii should be small at a SH of 0.003, it will be assumed that the dry regime was operative for all dropout classes for MP tape in Fig. 4.16. In the dry regime, there is no significant meniscus formation but dropout frequency should decrease due to any additional water condensed on the surfaces which gives better lubricity. Dropout frequency was significantly lower at 22 °C than at 32.2 °C for the 4-6 dB, 0.5-3 and 3-10 μs and 6-9 dB, 0.5-3 and 3-10 μs classes of dropouts, and dropout frequency for all other dropout classes was similar at each temperature or higher at 22 °C than at 32.2 °C. At a constant SH of 0.003, dropouts caused by smaller particles were less at lower temperature, which if the dry lubrication regime was operative, suggests that more water vapor condensed on the head and tape surfaces at lower temperature. The competing mechanism of increased lubricant mobility at higher temperature apparently led to reduction of larger dropout frequencies (which were caused by larger particles) at higher temperature. Even though MP tape is not topically lubricated, some lubricant is included in the tape formulation. Lubricant
Figure 4.16. Effect of temperature on dropout frequency in various classes of dropouts for wavy non-DLC ME tape and MP tape at a specific humidity of 0.003 during the first play/rewind cycle. Note that the given temperature was maintained during both the record pass and the first play/rewind cycle.
mobility affected larger dropout classes more than smaller dropout classes for wavy non-DLC ME tape at a SH of 0.003, and this is apparently also true for MP tape.

Figure 4.17 shows the effect of temperature on dropout frequency in various classes of dropouts for wavy non-DLC ME tape at a SH of 0.013 under equilibrium conditions. Spontaneously formed water menisci between the surfaces at a SH of 0.013 should be larger than those present at a SH of 0.003, and consequently, the temperature effect on menisci radii should affect dropout frequencies more than at a SH of 0.003. Based on data for wavy non-DLC ME tape in Figs. 4.14 and 4.15, it will be assumed that smaller dropout classes were in the partially flooded regime and that larger dropout classes were in the meniscus regime. Thus, larger menisci radii should reduce smaller dropout frequencies and increase larger dropout frequencies. The competing mechanism of improved lubricant mobility at higher temperature which reduced all dropout frequencies (especially larger dropout classes) at a SH of 0.003 could also be operative, but its effect should be less important at a SH of 0.013. Dropout frequency was lower at 22 °C than at 32.2 °C for all of the 4-6 and 6-9 dB classes, whereas, they were higher at 22 °C than at 32.2 °C for the 9-12 and >12 dB classes. This is consistent with larger menisci radii at 22 °C and better lubricant mobility at 32.2 °C.

The effect of temperature on dropout frequency in various classes of dropouts for MP tape at a SH of 0.013 under equilibrium conditions is shown in Fig. 4.17. Based on data for MP tape in Figs. 4.14 and 4.15, it will be assumed that smaller dropouts were in the partially flooded regime and that larger dropouts were in the meniscus regime. Thus, larger menisci radii should reduce smaller dropout frequencies and increase larger dropout frequencies. In the case of MP tape, the competing mechanism of increased lubricant mobility at higher temperature should not be as important as it is for topically lubricated wavy non-DLC ME tape, particularly at a SH of 0.013. Dropout frequency was lower at 22 °C than at 32.2 °C for all of the 4-6 dB, 6-9 dB, 0.5-3, 3-10 and 10-20 μs classes of dropouts, and dropout frequency for most of the larger dropout classes were higher at 22 °C than at 32.2 °C. This is consistent with larger menisci radii at 22 °C than at 32.2 °C.

Figure 4.18 shows the effect of SH on dropout frequency for 6-9 dB, 10-20 μs dropouts for wavy non-DLC ME and MP tapes at temperatures of 22 and 32.2 °C. The 6-9 dB, 10-20 μs class of dropouts was chosen for illustration because considering both tapes all lubrication regimes were operative over the given range of SH for this class of dropouts. Various lubrication regimes for the tapes are illustrated and generally progressed from dry to meniscus to partially flooded to fully flooded as SH was increased.
Figure 4.17. Effect of temperature on dropout frequency in various classes of dropouts for wavy non-DLC ME tape and MP tape at a specific humidity of 0.013 during the first play/rewind cycle. Note that the given temperature was maintained during both the record pass and the first play/rewind cycle.
Figure 4.18. Summary of the effect of specific humidity on dropout frequency for wavy non-DLC ME tape and MP tape (a) at two temperatures and (b) for two classes of dropouts at a temperature.
in each case. For the given class of dropouts, the dry regime was operative only for MP tape, whereas, the fully flooded regime was operative only for wavy non-DLC ME tape. It is reasonable to assume that spacing loss dropouts of a given depth and duration are caused by wear debris particles of about the same size for wavy non-DLC ME tape and MP tape based on the Wallace equation. Absence of the dry regime and presence of the fully flooded regime for wavy non-DLC ME tape is probably due to 5-10 nm of topical lubricant on the wavy non-DLC ME tape surface. Lubrication is provided by both the topical lubricant and spontaneously formed water menisci in the case of wavy non-DLC ME tape. Dropout data in Fig. 4.18 (a) show that dropout frequency for wavy non-DLC ME tape is about an order of magnitude larger than that of MP tape.

Figure 4.18 (b) shows the effect of SH on dropout frequency for 4-6 dB, 10-20 µs and 6-9 dB, 10-20 µs dropouts for wavy non-DLC ME tape and MP tape at a temperature of 22 °C. The 4-6 dB, 10-20 µs and 6-9 dB, 10-20 µs classes of dropouts were chosen for illustration because they were likely caused by wear debris particles of different size based on data in Fig. 4.14. The 4-6 dB, 10-20 µs class of dropouts was likely caused by wear debris particles smaller (60-90 nm diameter) than those which caused the 6-9 dB, 10-20 µs class of dropouts (>90 nm diameter) based on the Wallace equation. At a given SH with given mean Kelvin radius, the ratio of the mean Kelvin radius to the wear debris particle size should be larger for 4-6 dB, 10-20 µs dropouts as compared to 6-9 dB, 10-20 µs dropouts. For a given tape, various lubrication regimes should be operative in a given range of SH depending on the depth and duration of the dropout class. Lubrication regimes associated with larger ratios of menisci radii to particle size should be operative at larger values of SH than those associated with smaller ratios. Data for wavy non-DLC ME tape in Fig. 4.18 (b) show that the partially flooded regime was operative from 0.003 to 0.013 SH for 4-6 dB, 10-20 µs dropouts, whereas, the meniscus regime was operative from 0.003 to 0.009 SH and the partially flooded regime was operative from 0.009 to 0.013 SH for 6-9 dB, 10-20 µs dropouts. Data for MP tape in Fig. 4.18 (b) show that the meniscus regime was operative from 0.003 to 0.013 SH for 4-6 dB, 10-20 µs dropouts, whereas, the dry regime was operative from 0.003 to 0.009 SH and the meniscus regime was operative from 0.009 to 0.013 SH for 6-9 dB, 10-20 µs dropouts. Thus, experimental results confirm the effect of wear debris particle size on the operative lubrication regime.

Figure 4.19 shows streaming mode optimum operating envelopes within the data processing operating envelope in the SH-temperature plane for wavy non-DLC ME tape and MP tape. Optimum operating envelopes were constructed using head output and dropout frequency data in Figs. 4.12, 4.13, 4.14, 4.15, 4.16 and 4.17. High head output
Figure 4.19. Optimum operating envelopes in the specific humidity-temperature plane for wavy non-DLC ME and MP tapes during streaming mode experiments.
and good tape stability were considered to be desirable operation criteria in constructing the envelopes. The operating envelope for wavy non-DLC ME tape lies between SH values of 0.009 and 0.013 and spans the entire temperature range of 15.6 to 32.2 °C. Low head output at low SH and tape instability at high SH are a deterrence to using wavy non-DLC ME tape in low or high SH environments. The operating envelope for MP tape lies between 15.6 and 24 °C and spans a range of SH from 0.003 to 0.013. Tape instability and low head output at higher temperatures are a deterrence to using MP tape in high temperature environments. It is recommended that the tapes be used in the given optimum operating envelopes for the best tribological and magnetic performance during streaming mode operation.

4.4 Flat and Wavy ME Tapes and MP Tape

Figure 4.20 shows real time response of head output and friction force to changes in RH for ME tapes with and without a DLC coating and MP tape at temperature 22 °C. In these non-equilibrium experiments, the first minute of the experiment was in an equilibrium condition at 45% RH, and then, RH was modulated in one cycle of a square wave (unless tape failure occurred during the modulation) before finally being held again for one minute at 45% RH. Head output level and friction force were measured throughout each experiment.

Head output and friction force generally modulated in phase with RH for all of the tapes. Thus, addition and removal of water vapor in real time, since it changed head output and friction force according to RH, shows that the amount of water vapor in the air and condensed on the interface components directly affected head-to-tape spacing and the tribological behavior of the interface. According to the model developed in section 4.2, reduced head-to-tape spacing and higher friction force at higher RH or SH resulted from increased meniscus formation between contacting asperities on the head, tape and debris particle surfaces which increased normal and friction forces.

It is interesting to note that in these non-equilibrium experiments, that tape failure occurred due to high friction force for flat ME tapes with and without a DLC coating when RH was increased to about 80%. Difference of variations in friction force with changing RH for wavy non-DLC ME tape and MP tape as compared to flat ME tapes with and without a DLC coating suggests that either contact angles with water or bearing ratio curves for the tapes are different. Macroscopic contact angle for water drops on the tapes is the same and about 85° for all of the tapes. Figure 4.21 shows bearing ratio plots
Figure 4.20. Real time response of head output and friction force to non-equilibrium changes in relative humidity for ME tapes with and without a DLC coating and MP tape at temperature 22 °C during the first play/rewind cycle (note 0 dB is the initial playback rms voltage for each tape and 45% RH and vertical arrows indicate tape failure). Only wavy tape survived cycling of relative humidity.
Figure 4.21. Bearing ratio plots from a non-contact optical profiler at a scan size of 250 × 250 μm for virgin ME tapes with and without a DLC coating and MP tape.
for the virgin tapes. Bearing ratio curves are similar for flat ME tapes with and without a DLC coating and lie to the left of bearing ratio curves for wavy non-DLC ME tape and MP tape. Thus, available bearing area closer to the highest point on a tape for coupling the tape and head surfaces via menisci is larger for flat ME tapes as compared to wavy ME tape and MP tape. All of this implies that more menisci should form between the head and tape surfaces as RH is increased for flat ME tapes with and without a DLC coating as compared to wavy non-DLC ME tape and MP tape. In section 4.3.2, menisci heights at 22°C were determined to be on the order of 30 to 40 nm at 80% RH. Menisci of this size enables coupling of the head surface to areas of the tape 30 to 40 nm away from the highest point on the tape.

Meniscus heights on the order of tens of nanometers measured in this dissertation suggests that RH and SH in the head-to-tape contact interface are near saturation and higher than that maintained in the environmental chamber. A peak local water vapor pressure near the head gap in the head-to-tape contact interface 2 to 3 times larger than ambient water vapor pressure would explain this result. This water vapor pressure is comparable to that obtained if the local peak air and water vapor pressure were on the order of the average contact pressure at the contact region of the head and tape of 300 kPa. This is conceivable if there is any local air bearing effect between the head and tape near the head gap. High local water vapor pressure essentially moves one towards the liquid phase in the solid-liquid-vapor phase state diagram of water in the pressure-temperature plane.

Increased meniscus formation with increasing RH in the case of flat ME tapes with and without a DLC coating leads to a rapid increase in friction force and subsequent tape failure. For instance in Fig. 4.20, rapid increase in RH from about 20 to 80% began at about 350 s. As RH increased, friction force increased rapidly to about 11 mN and 30 mN for flat ME tapes with and without a DLC coating, respectively. Friction force for wavy ME tape increased only to about 8 mN during this time.

Variation in head output as normal and friction forces increase is related to asperity compliance or interfacial spring constant. Head output data in Fig. 4.20 indicate that among flat ME tapes, interfacial spring constant is larger for the tape with DLC coating. This is seen over the interval of time during which RH was rapidly increased from about 20 to 80%. Head output for flat ME tape without DLC coating increased about 2 dB during this time interval which corresponds to a reduction in head-to-tape spacing of about 20 nm based on the Wallace equation. Head output for flat ME tape with DLC coating increased by only about 0.5 dB during this time interval which corresponds
to a reduction in head-to-tape spacing of about 5 nm based on the Wallace equation. Large reduction in head-to-tape spacing for flat ME tape without DLC coating allowed more menisci to form between the head and tape surfaces which further increased friction force to a very high value of about 30 mN at tape failure.

Figure 4.22 shows the effect of SH on dropout frequency for 6-9 dB, 10-20 μs dropouts for ME tapes with and without a DLC coating and MP tape at temperatures of 22 and 32.2 °C. In these equilibrium experiments, dropout frequency was measured at various combinations of SH and temperature. In sections 4.2 and 4.3.2, four lubrication regimes were defined for wear debris particles passing through the contact interface. The four lubrication regimes are: dry, meniscus, partially flooded and fully flooded. Higher SH reduces dropout frequencies in the dry regime due to better lubricity of the surfaces. The meniscus regime is characterized by higher dropout frequencies with increasing SH, due to the appearance and disappearance of meniscus forces, depending on the orientation or extent of deformation of a wear debris particle in the contact interface. In the partially flooded regime, higher SH decreases dropout frequencies as larger mean Kelvin radius allows more menisci to maintain themselves around wear debris particles independent of their orientation or extent of deformation. The fully flooded regime is characterized by higher dropout frequencies with increasing SH due to menisci formation between the head and tape surfaces themselves due to mean Kelvin radius on the order of the summit-to-valley distance of the tape.

The 6-9 dB, 10-20 μs class of dropouts was chosen for illustration because considering the four tapes all lubrication regimes were operative over the given range of SH for this class of dropouts. Various lubrication regimes for the tapes are illustrated in Fig. 4.22. In section 4.3.2 with wavy non-DLC ME and MP tapes, lubrication regimes generally progressed from dry to meniscus to partially flooded to fully flooded as SH was increased in each case. For the given class of dropouts and the tapes used in this study, the dry regime was operative only for flat ME tape with a DLC coating and MP tape. Absence of the dry regime for wavy and flat ME tapes without a DLC coating is probably due to the 10 nm of topical lubricant on each tape surface. At 22 °C, flat ME tapes with and without a DLC coating were in the fully flooded regime from 0.009 to 0.013 SH, whereas, wavy ME tape without a DLC coating was in the partially flooded regime, and MP tape was in the meniscus regime, for the same transition in SH.

Bearing area curves in Fig. 4.21 show that available bearing area closer to the highest point on a tape for coupling the tape and head surfaces via menisci is larger for flat ME tapes with and without a DLC coating as compared to wavy ME tape without a
Figure 4.22. Effect of specific humidity on dropout frequency in the 6-9 dB, 10-20 μs class of dropouts for ME tapes with and without a DLC coating and MP tape at two temperatures.
DLC coating and MP tape. Thus, the onset of the fully flooded regime and severe tape instability occurs at a smaller SH for the flat tapes as the given Kelvin radius is sufficient to couple the head surface to the entire bearing area of the flat tapes. At 32.2 °C, all of the ME tapes were in the fully flooded regime from 0.013 to 0.021 SH, whereas, MP tape was in the partially flooded regime over the same transition in SH. Sudden onset of the partially flooded regime without the general progression through the four previously defined lubrication regimes is a characteristic of smoother tapes with smaller summit-to-valley distance and narrow bearing area curves. A streaming mode operating envelope within the data processing operating envelope in the SH-temperature plane was constructed for wavy non-DLC ME tape in section 4.3.2. It was recommended that wavy non-DLC ME tape be operated between SH values of 0.009 and 0.013 over the temperature range of 15.6 to 32.2 °C. Based on this study, the same envelope is recommended for flat ME tapes with and without a DLC coating, with the exception that from 15.6 to 24 °C, RH should not exceed 50% to avoid the fully flooded regime and severe tape instability.

4.5 Summary

Operating environment affected tribological and magnetic performance of the tapes. At a given temperature, higher SH increased normal and friction forces and decreased head-to-tape spacing due to spontaneous water meniscus formation between contacting and non-contacting asperities on the head, tape and debris particle surfaces. Dropout frequency and interface stability were sensitive to both SH and temperature. Humidity dependence was governed by the relative size difference between wear debris particles and spontaneously formed water menisci. Competing mechanisms of increased lubricant mobility and spontaneously formed water menisci of smaller radii of curvature at higher temperature governed temperature dependence. Bearing ratio curves and lubricant thickness for the tapes determine available tape area for coupling of capillary condensed water menisci to the magnetic head surface which determines the onset of high friction and tape instability at high humidities. DLC coating increases the interfacial spring constant due to less asperity compliance.

A model based on capillary condensation of water vapor onto surfaces in a sliding contact explains trends observed in experimental data. An expression for meniscus force consisting of both Laplace and surface tension contributions is developed for nanometer size contact spots and wear debris particles. The model predicts that meniscus force will
increase and head-to-tape spacing will decrease with increasing SH which was observed experimentally. Four lubrication regimes are defined for wear debris particles passing through the contact interface. Both SH and extent of deformation or orientation of a particle determine whether menisci will form around the particle, and presence or absence of associated meniscus forces explains trends in dropout frequency data. The model allows determination of meniscus height from which minimum values of Kelvin radius and RH in the contact interface can be calculated.

Meniscus heights on the order of tens of nanometers were measured and predicts that RH and SH in the head-to-tape contact interface are near saturation and higher than that maintained in the environmental chamber. High local pressure in the head-to-tape contact region may arise from the fact that there is high hydrodynamic pressure there, which increases the water vapor pressure available for condensation. A peak local water vapor pressure near the head gap in the head-to-tape interface 2 to 3 times larger than ambient water vapor pressure would explain this result, and this water vapor pressure is comparable to that obtained if the peak local air and water vapor pressure were on the order of the average contact pressure of 300 kPa at the contact region of the head and tape. The optimum operating envelope for ME tape lies at moderate humidity, whereas, for MP tape it lies at low temperature. Avoiding the fully flooded regime may prove to be the most stringent design requirement for good interface stability and low dropout frequency as tapes become smoother in future ultra-high density magnetic tape recording systems.
CHAPTER 5

POLE TIP RECESSION AND DIFFERENTIAL WEAR IN THIN-FILM TAPE HEADS

5.1 Background

5.1.1 Alternate Pole Tip Materials

Thin-film magnetic heads are commonly used for high-density magnetic recording in data-processing tape and disk drives. For thin-film heads using magnetoresistive (MR) head technology, the read head is MR type and the write head is inductive. The body of a thin-film head is made of magnetic ferrites or nonmagnetic alumina-titanium carbide (Al₂O₃-TiC), and the head construction includes coatings of soft magnetic alloys, insulating oxides and bonding adhesives. The major problems in thin-film recording heads are pole tip/head gap recession in the inductive heads, and scratching/smearing, electrical short, electrostatic charge buildup and corrosion of the MR stripe in MR read heads (Bhushan, 1992; Bhushan, 1996). In inductive heads with magnetic cores (such as Ni-Zn ferrite), some newer head designs utilize a single thin-film pole tip per track, whereas, heads with a nonmagnetic core (such as Al₂O₃-TiC) utilize two pole tips per track, which results in a wider thin-film structure, and PTR becomes even a bigger problem. PTR causes signal degradation due to spacing loss and can be minimized by matching as closely as possible the mechanical properties of the magnetic poles and insulating layers with the harder substrate material.

Plated nickel iron (NiFe) is the most commonly used pole material for tape and disk heads (Chikazumi and Charap, 1964; Cullity, 1972), but is softer than the hard head substrate material and a family of insulating layers and the head gap (e.g. Al₂O₃ and SiO₂) used in the head construction which leads to PTR (Bhushan, 1996). Cobalt zirconium tantalum (CoZrTa) amorphous film is also commonly used in disk heads and is expected to be used in tape heads (Shimada and Kojima, 1982; Yamada et al., 1984; Tago
et al., 1985; Su et al., 1988; Wang et al., 1990; Arai et al., 1992; Jursich et al., 1996).

New pole materials such as a family of iron based alloys (primarily Fe-N based) and others are being developed for high density applications because their high saturation magnetization \( M_s \) or saturation flux density is needed to write on high coercivity media (Hayashi et al., 1988; Katori et al., 1989; Wang and Kreider, 1990; Ishiwata et al., 1991; Okumura et al., 1992; Bain and Kreider, 1995; Bain et al., 1996). Several papers review recent developments in thin-film material development, see (Jagielinski, 1989; Kohmoto, 1991; Hayakawa, 1994). Iron aluminum nitride (FeAlN) is one of the materials in which Al is used for thermal stability, and the Al content is minimized to improve mechanical properties. Nitrogen flow rate and substrate temperature during deposition are optimized to get low coercivity, high permeability, low magnetostriction and high mechanical properties. High \( M_s \) for a pole material is beneficial for producing a high fringing magnetic field strength across the head gap without saturating the head, and allows the head to be operated in a wider linear region (where the fringing magnetic field strength is linear with respect to the coil current) to higher magnetic inductions without saturating the head.

Saturation magnetization \( 4\pi M_s \) values of NiFe, CoZrTa and FeAlN films are about 8-10, 12-14 and 19-20 kG, respectively. Soft head materials are required to have low coercivity \( H_c \) and high permeability. For an applied field \( (H_k) \) at which saturation is reached in the \( M-H \) loop, the average permeability is equal to \( M_s/H_k \) which is on the order of 5 kG/Oe for NiFe films. Coercivity of NiFe is on the order of 0.1 to 1 Oe. Initial permeabilities (i.e. the values at very low fields) of NiFe, CoZrTa and FeAlN films are on the order of 2, 1-2 and 4 kG/Oe, respectively. These values are much smaller than that of bulk materials (Chikazumi and Charap, 1964; Cullity, 1972). Average permeability of fabricated heads with NiFe, CoZrTa and FeAlN magnetic films are on the order of 0.3-1, 0.8 and 0.3 kG/Oe, respectively. Low values of permeability of FeAlN heads may result from anisotropy in the sloping region due to oblique angle of incidence sputtering. FeAlN is nanocrystalline with crystalline sizes ranging from 10 to 30 nm (desirable to have small size). Its processing is not well developed and is difficult to control, and there is a small window of parameters which yields optimum magnetic properties. Whereas, NiFe and CoZrTa thin-films are easy to produce with well developed processes, and plated NiFe is very inexpensive to produce. The mechanical, wear and corrosion properties of thin-films of the new pole tip materials and their PTR behavior when these materials are used as the pole material in inductive heads have not been systematically studied to date (Tago et al., 1985; Ohmae et al., 1986; Kohmoto et al., 1989; Ishiwata et al., 1991; Ishiwata et al.,
The goal of future drives with a volumetric density of 0.6 GB/cm$^3$ (one terabyte per cubic inch) is to limit the growth of PTR to about 10 nm in 1000 h of normal operation (=18,000 km of tape over the head @ 5 m/s) with a mechanical spacing of < 25 nm, wrap angle of 2.9° per side, head radius of 8 mm and at a tension of about 0.56 N over a 12.7-mm wide tape (with about a 4 μm substrate). NiFe pole tip heads are capable of PTR of about 25 nm. The high hardness of FeAlN can give reduced PTR. The objective of this study is to characterize the mechanical properties of materials being developed for use in advanced thin-film heads using a depth-sensing nanoindenter and to conduct functional tape drive tests with dummy heads with thin-film head structure in which growth in PTR is monitored using AFM imaging. The tests were conducted with rather intimate contact of the tape and head surfaces for test durations of 1000 km under accelerated conditions.

5.1.2 Hard Carbon Coatings

PTR and other damage to the head structure, which may result in signal degradation, can be minimized by depositing a thin (~5 to 20 nm) hard carbon coating over the entire ABS, including the head structure. Sputter deposited carbon coatings are currently used in MR heads. Cathodic arc and direct ion beam deposition techniques are highly energetic processes which are known to produce a dense and hard coating with good adhesion to the substrate (Bhushan, 1995). Recent screening studies have shown that cathodic arc and ion beam carbon coatings are superior in mechanical properties and scratch and wear resistance to sputtered and PECVD carbon coatings (Bhushan, 1995). The objective of this research was to conduct functional tape drive tests with coated dummy Al$_2$O$_3$-TiC and Ni-Zn ferrite heads with thin-film head structure.

5.2 Alternate Pole Tip Materials

5.2.1 Micromechanical Characterization

Mechanical properties data obtained from a nanoindenter are compared in Fig. 5.1. Details of the coupon samples and experimental techniques can be found in a separate paper (Patton and Bhushan, 1996c). The sputtered NiFe coating exhibits a
hardness of about 9 GPa at an indentation depth of 20 nm at peak load, and an elastic modulus of 280 GPa. Hardness of CoZrTa coating is slightly lower than that of NiFe but elastic modulus is much lower (180 GPa). The FeAlN coating exhibits a higher hardness of 18 GPa and an elastic modulus of 300 GPa. At these indentation depths, the alumina underlayer does not influence the mechanical properties of the pole tip material coating on the surface. However, the mechanical properties change at large indentation depths because of the underlayer. Since plated Ni$_8$Fe$_{20}$ (with small additions) is used in the construction of heads, its properties were also measured for comparison. It was found that its properties are slightly inferior to that of sputtered NiFe, but are much better than the historical data of 230 HV for hard permalloy with 3% Ti or Nb (Bhushan, 1996). Hardness and elastic modulus of 0.25-μm thick PECVD diamondlike carbon or DLC (proprietary 3M process) were also measured and these were 16 GPa and 160 GPa, respectively. DLC coatings are preferred for MR heads because they dissipate heat more readily than Al$_2$O$_3$.

During scratch tests, NiFe and CoZrTa coatings exhibited a continuous increase in friction with normal load which indicates that the tip ploughed into the coating even at the lowest load of 2 mN, and were damaged from the beginning during scratching. Whereas, for the FeAlN coating, the coefficient of friction started out low and remained low until an abrupt increase at a critical load of about 8 mN. This indicates that at first the tip slid over the surface with no ploughing, and after exceeding the critical load, a brittle fracture occurred with a corresponding increase in friction.

5.2.2 Tape Drive Tests

Figure 5.2 shows 3-D and averaged 2-D AFM scans across the thin-film structure for a head with Ni-Fe pole tips after being run against 5 km of MP tape. The 2-D line scan is the averaged (longitudinally along thin-film region) cross section of the 3-D profile. The 3-D and 2-D scans shows that the entire thin-film region is recessed from the Al$_2$O$_3$-TiC ABS, and the depth of recession from the ABS varies for the different thin-films. Excellent uniformity of recession is observed longitudinally along the thin-film region in the 3-D profile. As shown in the averaged 2-D profile, PTR is defined to be the vertical distance between the substrate nearest the pole and the pole itself.

Figure 5.3 shows 3-D AFM scans across the thin-film structure for NiFe and FeAlN heads at various stages of being run against MP tape. The virgin profiles of both the NiFe and FeAlN heads show that debris accumulated on the glue line between the
Figure 5.1. Comparison of hardness and elastic modulus at a 20 nm indentation depth at peak load, and critical load during scratching for various thin-film structures and Al₂O₃-TiC substrate.
Figure 5.2. 3D and averaged 2D AFM scans across the thin-film structure for a NiFe head run against MP tape for 5 km.
Al₂O₃ overcoat and Al₂O₃-TiC substrate during the lapping process. This debris was tenacious in the sense that it could not be removed by wiping with a cloth soaked in isopropyl alcohol. During the first 5 km of sliding, the debris was removed from both the NiFe and FeAlN heads by the rubbing action, and growth of PTR occurred for the NiFe head. The 3-D profiles after 1000 km of running show further growth in PTR for the NiFe head, whereas, PTR for the FeAlN head remained constant. Differential wear between the softer Al₂O₃ and harder TiC phases of the two phase Al₂O₃-TiC substrate is seen for both NiFe and FeAlN heads after 1000 km of sliding distance. The harder TiC phase of the two phase Al₂O₃-TiC substrate is not expected to wear as much as the Al₂O₃ phase. This kind of differential wear of the ABS is problematic in the sense that hard TiC protrusions may cause excessive tape wear.

Figure 5.4 (a) shows the PTR versus sliding distance for NiFe, CoZrTa and FeAlN heads. FeAlN poles exhibited a low (~10 nm) and constant PTR over 1000 km of sliding distance, whereas, NiFe and CoZrTa exhibited growth in recession from 22 and 12 nm to 33 and 37 nm, respectively (±σ error bars represent variability in the average PTR at different measurement locations on the heads). Softer NiFe and CoZrTa experienced about 50% of their total growth in PTR in the first 10 km of sliding distance (~1% of total sliding distance), and the data suggest that PTR is approaching a saturated value for each material during the test. Comparison of the mechanical properties of the three pole materials in Fig. 5.1 suggest that the higher hardness and/or higher critical load for scratch resistance prevent growth in PTR for FeAlN pole tips. The hardness of CoZrTa is comparable to that of NiFe but its lower elastic modulus and toughness may be responsible for the highest PTR for CoZrTa after 1000 km of sliding distance. PTR of virgin NiFe and CoZrTa at 10 km of sliding distance were equal, further growth in PTR for CoZrTa did not begin until after 100 km, whereas, about 80% of the growth of NiFe PTR occurred during the first 100 km. The different behavior for the two very similar (in mechanical properties) materials will be explained subsequently.

Figure 5.4 (b) shows 2-D AFM line scans across the thin-film structure at various sliding distances for NiFe, CoZrTa and FeAlN heads. The 2-D AFM line scans show that the entire thin-film region became more recessed from the ABS with increased sliding distance for NiFe and CoZrTa heads as compared to the lack of growth in recession observed with the FeAlN head. Tenacious debris accumulated on the glue line on the virgin heads seen as a hump on the 2-D line scans is seen to be removed by the rubbing action during the first 5 km of sliding distance. Differential wear of the Al₂O₃-TiC ABS appears as waviness in the 2-D profiles in Fig. 5.4 (b) at large sliding distances.
Figure 5.3. 3D AFM scans across the thin-film structure for NiFe and FeAlN heads at various stages of being run against MP tape.
Figure 5.4. (a) Pole tip recession vs sliding distance and (b) representative averaged 2D AFM line scans across the thin-film structure for NiFe, CoZrTa and FeAlN heads run against MP tape to various sliding distances.
Mechanisms of differential wear between dissimilar materials which causes PTR can be identified by inspecting Fig. 5.4 (b). In the case of the NiFe head, most of the growth in PTR occurred, and the Al₂O₃ overcoat recession remained essentially constant, in the first 50 km of sliding distance. This is evident in the 2-D line scans because the recession of the pole tips from the Al₂O₃ overcoat increased considerably over the first 50 km of sliding distance. From 50 km to 250 km of sliding distance, PTR was essentially constant, but Al₂O₃ recession increased considerably, see Al₂O₃ recession approach PTR in Fig. 5.4 (b). Differential wear of dissimilar materials appears to be governed by two factors, the relative hardness/scratch resistance of the materials, and their relative recession from the ABS. When either NiFe or CoZrTa recession was comparable to that of the Al₂O₃ overcoat, NiFe or CoZrTa were worn and became more recessed from the Al₂O₃ and ABS. This kind of differential wear can also be seen with respect to the pole tips and head gap for both NiFe and CoZrTa at 5 and 50 km of sliding distance, Fig. 5.4 (b). Hardness of Al₂O₃ is only slightly larger than that of NiFe and CoZrTa, but its scratch resistance is 5 times larger than that of NiFe and CoZrTa, which makes Al₂O₃ more wear resistant than NiFe and CoZrTa. Similar behavior is observed in the 2-D profiles of CoZrTa. Differences in the growth of PTR in the beginning stages of wear of NiFe and CoZrTa can now be explained using the 2-D profiles. The Al₂O₃ overcoat recession from the ABS at 5 km of sliding distance was less for the CoZrTa head than for the NiFe head. The less recessed Al₂O₃ overcoat protected the CoZrTa pole tips from wearing until the Al₂O₃ overcoat was worn to a similar recession to that of the CoZrTa pole tips at about 100 km, see Fig. 5.4 (a), at which time the softer pole tips began to wear again. 2-D profiles of the CoZrTa head in Fig. 5.4 (b) show that no growth in the recession of the Al₂O₃ overcoat occurred in the first 5 km of sliding distance, but considerable growth occurred from 5 to 50 km.

In the case of the FeAlN head, PTR remained constant, and the Al₂O₃ overcoat recession gradually increased, through 1000 km of sliding distance. Even though the critical load for scratching of Al₂O₃ is slightly larger than that of FeAlN, the hardness of FeAlN is about twice that of Al₂O₃ which makes FeAlN more wear resistant than the Al₂O₃. Thus, from 50 to 1000 km of sliding distance, the Al₂O₃ overcoat recession is larger than the PTR.

The mechanism of differential wear of dissimilar materials and PTR are now understood. If dissimilar materials are at about the same level of recession, the material with poorer mechanical properties (determined primarily by both the hardness and scratch resistance) will wear and become more recessed from the ABS. However, at some point
wear of this material will be reduced due to less severe lower contact pressure interactions with tape asperities and loose debris being raked across the thin-film region by the tape. The less recessed material with superior mechanical properties will now wear due to its more intimate (higher pressure) interactions with tape asperities and loose debris being raked across the thin-film region by the tape. When the materials approach a similar recession value, the cycle will begin again and the cyclic behavior will continue until both materials approach a saturated value of recession. Saturation occurs because a “safe” distance from the tape asperities is reached where the contact pressure of the interactions with tape asperities and loose debris being raked across the thin-film region is insufficient to cause appreciable wear of either material.

Neighboring materials in a thin-film structure can determine the recession behavior for a given film. This can be seen in the case of the Al₂O₃ overcoat in Fig. 5.4 (b). For CoZrTa and FeAlN heads, the initial recession of the Al₂O₃ overcoat from the ABS was similar. However, after running to 1000 km of sliding distance, the recession of the Al₂O₃ overcoat of the CoZrTa grew to a value (~30 nm) about twice that observed for the Al₂O₃ overcoat of the FeAlN head. The Al₂O₃ overcoat was exposed as a shoulder in the case of the CoZrTa head due to the rapid initial growth of PTR, see CoZrTa 2-D profile at 5 km and 50 km of sliding distance in Fig. 5.4 (b), which allowed it to be worn excessively compared to the Al₂O₃ overcoat of the FeAlN head which was protected by the FeAlN pole tips.

5.2.3 Summary

Based on nanoindentation and microscratch measurements, it is concluded that FeAlN coatings exhibit higher hardness and scratch resistance as compared to that of NiFe and CoZrTa coatings. The better mechanical properties of FeAlN pole tip material reduced PTR as compared to NiFe and CoZrTa in drive level tests using dummy heads. The mechanism of differential wear of dissimilar materials, which causes PTR, is now better understood. PTR is influenced not only by the pole tip mechanical properties, but also by the mechanical properties of other materials in the thin-film structure, as well as the relative recession of the various materials with respect to the ABS. An insulating under/overcoat and gap material should be chosen with the highest hardness and scratch resistance to further protect the pole tips and reduce PTR in future thin-film inductive heads. FeAlN family of materials can be further tailored to give optimum mechanical, tribological and magnetic properties.
5.3 Hard Carbon Coatings

5.3.1 Tape Drive Tests

Figure 5.5 (a) shows a comparison of the results obtained by running CrO$_2$ (rms = 17.1 nm, P-V = 161 nm) and MP tapes against uncoated Ni-Zn ferrite heads. CrO$_2$ tape caused a large pole tip recession and catastrophic wear of the thin-film region after only 5 km of sliding distance, whereas, MP tape produced smaller pole tip recession and relatively minor damage primarily in the form of scratching to the thin-film region after 500 km of sliding distance. MP tape was selected since this tape is considered for advanced thin-film head applications.

Figure 5.5 (b) shows a comparison of the performance of uncoated and ion beam carbon coated Ni-Zn ferrite heads during sliding experiments. The pole tip recession increased with sliding distance for the uncoated head, but remained essentially constant over a larger sliding distance for the coated head (error bars in the left block represent the variability in the average pole tip recession over the four chosen poles). The 2-D AFM line scans of the uncoated head show that the entire thin-film region recessed from the ABS with increased sliding distance. Optical micrographs of the coated head show that the coating remained on the pole tips through 1000 km of sliding distance which prevented growth of pole tip recession.

Figures 5.6 (a) and 5.6 (b) show a comparison of the performance of uncoated and ion beam carbon coated Al$_2$O$_3$-TiC heads during sliding experiments. The pole tip recession increased with sliding distance for the uncoated head, but remained essentially constant over a larger sliding distance for the coated head. The 3D [Fig. 5.6 (a)] and 2D [Fig. 5.6 (b)] AFM line scans show that the coating reduced the growth of recession of the entire thin-film region from the ABS with increased sliding distance as compared to that observed with the uncoated head. Optical micrographs in Fig. 5.6 (b) show that the coating remained on the pole tips through 1000 km of sliding.

Figure 5.6 (c) shows a comparison of the performance of uncoated and cathodic arc carbon coated Al$_2$O$_3$-TiC heads during sliding experiments. The performance of the cathodic arc carbon coated head in preventing pole tip recession was better than the uncoated head, but was less effective than the ion beam carbon coating. The 2-D AFM line scans and optical micrographs of the coated head show that the coating was removed from the pole farthest from the substrate (bottom pole in optical micrographs) after 160
Figure 5.5. Pole tip recession vs. sliding distance as measured with an AFM. AFM scans across the thin-film structure at various sliding distances and optical micrographs [(a) only] of the coated thin-film structure at various sliding distances for (a) uncoated Ni-Zn ferrite heads before and after being run against CrO₂ and MP tapes and (b) uncoated ion beam carbon coated Ni-Zn ferrite heads run against MP tape.
Figure 5.6. Pole tip recession vs. sliding distance as measured with an AFM. AFM scans across the thin-film structure at various sliding distances and optical micrographs [except (a)] of the coated thin-film structure at various sliding distances for (a) and (b) uncoated and ion beam carbon coated Al$_2$O$_3$-TiC heads run against MP tape and (c) uncoated and cathodic arc carbon coated Al$_2$O$_3$-TiC heads run against MP tape.
sliding between 5 and 100 km. Further growth in recession of this pole tip after 100 km observed with the uncoated head did not occur. Further note that wear of carbon coating, when it occurred, was initiated at the pole tips which is related to the adhesion of carbon to various layers present on the substrate. Finally, no loose debris was found on the thin-film region near the pole tips in tests with uncoated and coated heads.

5.3.2 Summary

Hard carbon coatings were deposited by cathodic arc and direct ion beam deposition techniques on thin-film Al₂O₃-TiC heads and by the latter technique on thin-film Ni-Zn ferrite heads. Functional accelerated tests were conducted against MP tapes in a linear tape drive. Ion beam carbon coatings on Ni-Zn ferrite and Al₂O₃-TiC heads substantially reduced the pole tip recession observed with uncoated heads. Cathodic arc carbon coated Al₂O₃-TiC heads performed better than uncoated heads, but were less effective than the ion beam coating. Pole tip recession increased only if carbon was removed from the pole tip. This suggests that coating effectiveness is determined by its adherence to the pole tip. In two-wide pole tip heads, wear of the pole adjacent to the substrate was less than that of the other pole. Coatings withstood accelerated tests and may meet life time requirements of future heads.
CHAPTER 6

CONCLUSIONS

6.1 Rotary Head Tape Drive

MP tape was found to be more durable than three kinds of ME tapes. DLC coating improved performance of ME tape in pause mode, but was unable to prevent lateral cracking brought on by longitudinal tension or flexing of the tapes in the transport. Friction and wear mechanisms of 3 body abrasion and adhesion were operative in the experiments. Generally, high friction and wear early on in play/rewind cycling experiments were brought on by loose wear debris present on the tape surface. Abrasion gave way to adhesion at high numbers of play/rewind cycles and wear rates became negligible. Thus, generation of loose wear debris and their presence in the sliding interface is the primary mechanism controlling friction and wear in the precision head-to-tape interface.

ME tapes with various surface texture and the same lubricant thickness had different friction and wear behavior. Origins of friction and wear for ME tape were found to be plastic deformation and brittle fracture. For a given asperity size, enough asperities should be present to prevent high strain of high asperities and associated plastic deformation and high friction. Smooth surfaces with high isolated asperities should be avoided to prevent brittle fracture of high isolated asperities (generation of loose wear debris particles) and high friction force and wear in the abrasive regime. A wear resistant and low friction surface with enough asperities to prevent plastic deformation and brittle fracture was discovered. An analytical model based on the principles of plastic deformation and brittle fracture was developed and combined with experimental data to determine the subtle origins of friction and wear.

Environmental effects were governed by the formation of capillary condensed water menisci at asperity contacts. Humidity, temperature and bearing ratio curves are all
important in determining the effects of environment. Key experimental observations include: high friction force and reduced head-to-tape spacing as RH is increased, the existence of well defined lubrication regimes depending on the relative size difference between water menisci and loose wear debris particles, and seizure or severe instability of tapes with narrow bearing ratio curves. An analytical model based on the Kelvin equation was developed to predict the effect of capillary condensed water vapor on the tribological behavior of the sliding interface. The model is in agreement with the experimental results.

6.2 Linear Tape Drive

To attain and maintain low PTR in advanced thin-film inductive write heads for tape recording applications, the usage of alternate pole tip materials with superior magnetic and mechanical properties, such as FeAlN, or application of hard carbon coatings over the head structure are recommended. In experiments, both of these techniques were able to prevent growth in PTR with sliding distance against MP tape. Mechanism of differential wear is intimately related to varying mechanical properties of different materials in a composite structure which is mitigated or eliminated with mechanically harder pole tip materials or application of a coating on the head structure.


