MICRO/NANOSCALE DIFFERENTIAL WEAR AND CORROSION OF MULTIPHASE MATERIALS

DISSERTATION

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By

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ABSTRACT

Wear of multiphase materials at the micro/nanoscale is important in devices such as magnetic tape and disk drives, where the thin-film read-write heads are multiphase. Differential wear, which is caused by differences in wear resistance among the head’s phases, causes thin-film poles to recede from the head’s bearing surface; this phenomenon is called pole tip recession (PTR). It is a problem because it increases spacing between the poles and medium, resulting in lower write density.

Here, PTR in tape heads is studied to understand micro/nanoscale differential wear. Test results suggest that three-body abrasion, which leads to primarily plastic wear, is the operative wear mode. Most of the three-body abrasive particles originate from the tape surface; the alumina head-cleaning agents (HCAs) in the tape, which function as load bearing particles at the interface, are the primary abrasives. Some particles originate from the head substrate.

PTR can be reduced by: lowering tape tension, choosing a substrate that is harder than the tape’s HCAs, choosing a pole material that is as close as possible to the hardness of the substrate, and lowering the thickness of the head’s thin-film region to a value as low as possible. Material hardness matching, i.e. choosing the substrate and pole materials such that their hardness values are close to equal, will not reduce PTR if a
substrate is chosen that is less hard than the HCAs. Covering the head with a diamond-like carbon (DLC) coating reduces PTR in the short term.

An analytical model that accounts for the observed wear is presented. The model shows that each of the following leads to higher differential wear: increasing the thickness of three-body particles, increasing tension, decreasing thin-film hardness, and increasing the thin-film wear coefficient. An increase in thin-film wear coefficient can be caused by an increase in thin-film thickness or an increase in the number of particles at the interface.

Battelle Class II and elevated temperature & humidity tests have been conducted to study corrosion of tapes and heads. The addition of DLC coatings increases the corrosion resistance of heads; the coating inhibits contact between environmental pollutants and the metal surfaces.
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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 Definition and Importance of Micro/Nanoscale Differential Wear of a Multiphase Material / Pole Tip Recession in Linear Tape Heads

A multiphase material is any that consists of more than one discrete material in the makeup of its structure. In fact many engineering materials are multiphase. Metal alloys and steels consisting of more than one of its different phases, e.g. ferritic - pearlitic or ferritic - martensitic, can be considered multiphase. Artificial multiphase materials, known as composites, are also common. In composites, materials, usually of different material groups, are combined so that the resulting material possesses some of the advantages of the constituent materials. At the same time, some of the constituents' poor qualities are suppressed. As the qualifications for material and other properties in applications become more stringent, multiphase materials will be used more often since they give the material designer great control over properties. As their use becomes more frequent, an understanding of multiphase materials' tribological behavior becomes important.

Differential wear behavior has not been modeled on the micro/nanoscale. One application in which micro/nanoscale differential wear is especially important is in
magnetic tape and disk drives. Tape heads are multiphase by necessity; it is required for them to properly perform their mechanical and magnetic functions. In inductive heads, relatively hard (typically ceramic) phases are used as substrates because they are highly wear resistant, while relatively soft magnetic metal pole phases and insulating thin films are used for their good magnetic properties. Differential wear, which is caused by differences in wear rates among the different phases (produced by the differing wear resistance of the phases), causes pole pieces in heads to recede from the air bearing surface or substrate. This increased spacing results in lower write density. Wallace (1951) gives a general expression for the reproduced signal amplitude for a sinusoidal recording. The amplitude of that expression is proportional to a spacing loss term:

\[ e(t) \propto S(\lambda) = \text{separation loss} \]

\[ = \exp(-2\pi d/\lambda) \]

(1.1)

where

\[ d = \text{effective spacing between the head and medium} \]

\[ \lambda = \text{recorded wavelength} \]

The other factors in the equation relate to properties of the head, medium, or the drive. This physical spacing between the pole and the substrate, or air bearing surface, is referred to as pole tip recession (PTR). In this work, PTR in tape heads is studied to understand micro/nanoscale differential wear.

A schematic of a thin-film inductive head showing the definition of PTR is presented in Figure 1.1. All of the shaded and hatched regions in the figure depict materials that are deposited as thin films. The thin-film region (the region where the writing to media actually takes place) consists of an undercoat, north and south magnetic
Figure 1.1: Cross-section schematic of a thin-film inductive head showing PTR and overcoat recession and an actual AFM profile of this same region.
poles, a gap (between the poles), and an overcoat. The function of the undercoat is to “planarize” the relatively rough substrate wafer so as to deposit the poles on top of it. The rest of the structure is deposited on top of the undercoat. Since the substrate can be electrically conductive, the undercoat also tends to insulate the copper coils from the substrate. After the poles are deposited the film is not planar, so a relatively thick overcoat must be deposited to create a planar surface so that the substrate closure can be glued on. Also shown in Figure 1.1 is an actual atomic force microscope (AFM) profile across the thin-film region of a head. An AFM, which is discussed in detail in Appendix B, is an extremely sensitive profilometer (among other functions), with a vertical resolution of approximately 0.1 nm. These types of profiles are shown in Chapter 3 and are used in this work to measure PTR and overcoat recession. PTR in modern tape heads is normally on the order of tens of nanometers. It is important to keep in mind that these profiles are not to scale. The vertical scale is magnified with respect to the horizontal by approximately 520 times.

Interestingly, tape heads generally start with a nonzero PTR. An initial PTR of ten to twenty nanometers is fairly typical for current high-end tape heads. This initial PTR is also a result of differential wear. In this case it occurs in contour lapping during head manufacturing (Bhushan, 1996, 2000; Lakshmikumaran et al., 2000). Optimization of this contour lapping process (for the minimization of tape lapping, which is currently used to reduce PTR in manufacturing) is the subject of recent research (Granger et al., 2000). Factors such as lubrication and abrasive particle slurry type were found to be important.
It is useful here to discuss the interface and the tape head counterface, namely magnetic tape. In modern drives, the head is separated from the tape by an air film on the order of tens of nanometers thick during operation. The thickness of this air film is a function of tape speed, tension, tape stiffness, and head geometry. The two governing equations are known as the Reynolds equations for gas-lubricated bearings and the tape bending equation (Stahl et al., 1974; Hamrock, 1994). Tape head surfaces may be engineered, by the inclusion or exclusion of machined slots, etc., to control the air film thickness.

Magnetic tapes are laminates that consist of a base film layer, usually polyethylene terephthalate (PET), a magnetic layer, and a backcoat (the use of which is optional) (Bhushan, 2000). See Figure 1.2. Two types of magnetic layers are common: polymeric magnetic layers and thin-film layers. The polymeric magnetic layer, used in particulate tapes, consists of magnetic particles and, in some cases, head cleaning agents (HCAs) that act as bearing surfaces and keep the head clean, dispersed in a polymeric matrix. This is then coated onto the substrate. The polymeric matrix consists of a binder, which holds the magnetic particles in place, and a lubricant, typically a fatty acid ester. The polymeric magnetic layer is the most widely used. Co-modified $\gamma$-$\text{Fe}_2\text{O}_3$ and metal particle (MP) tapes are common examples. MP tapes are used extensively in the work reported in this dissertation. MP tape consists of submicron sized needle-shaped passivated iron magnetic particles, HCAs, which are generally 200-300 nm diameter $\text{Al}_2\text{O}_3$ particles, and 200-300 nm diameter conductive carbon particles, which are used to improve friction and wear properties, dispersed in a polymer formulation of binder and fatty acid ester lubricants. Current MP magnetic particles generally have a length of
Figure 1.2: Cross-sectional view of a magnetic tape

about 100-200 nm and an aspect ratio of five to ten. A non-magnetic coating is often deposited before the magnetic layer. This layer, which is used as a leveling device for very thin magnetic layers, consists of ultra-fine TiO$_2$ of about 35 nm diameter with the same conductive carbon and lubricant deposited in the same binder, as in the magnetic layer. This allows for a smoother and thinner magnetic layer. Another kind of magnetic tape consists of a continuous film of magnetic material vacuum deposited (usually evaporated) onto the base film. A topical lubricant is applied to the surface. Metal evaporated (ME) tape is a thin-film tape. ME tape uses a magnetic layer composed of a continuous thin film of Co-Ni-O evaporated onto a tape substrate. Current ME tapes use a diamond-like carbon (DLC) coating for increased tape wear and corrosion durability. ME tapes also use a topical perfluoropolyether lubricant on the front and back coats. Since the magnetic layer of this kind of tape is thinner and smoother than a magnetic
particle layer, and since its magnetic properties are generally better, some hope that ME tapes can be used for future high-density applications. For now, they are much less commonly used than MP tapes.

Wear of magnetic materials (Katori et al., 1994) and differential wear of magnetic materials and head substrates (van Groenou et al., 1990; Ura et al., 1993; Tsuchiya and Bhushan, 1995; Gupta and Bhushan, 1995; Jursich et al., 1996; Patton and Bhushan, 1996; Bhushan et al., 1997; Harrison et al., 1998; Sourty et al., 2000) have been observed and measured by numerous authors. Tsuchiya and Bhushan (1995) proposed a wear mode for PTR. They proposed that wear particles from the soft thin-film region of the head are initially produced. These particles, of course, may also originate from the tape; HCAs, which are alumina particles used in the formulation of MP tape, are certainly hard enough to cause wear of the thin-film region. These particles are trapped at the interface and result in growth of PTR by three-body abrasion. (Three-body abrasion is defined and discussed in section 1.4.) They suggested that three-body abrasion must be the wear mode for PTR because tape asperities are not able to reach the recessed thin-film surface of the head to a significant extent; tape asperities are not large enough to reach the recessed material and the tape cannot bend into the recess. They verified this proposition by experiment, using an optical interference technique to measure differences in real area of contact in tape contact with the top surface and in tape contact with a fabricated recess. The real area of contact was much lower over the area of the recess, implying that wear of the recessed region cannot occur by direct contact with the tape. This is discussed in
more detail in Chapter 3. Three-body abrasive wear modes for PTR are also proposed for
tape heads and disk heads by Harrison et al. (1998) and Xu and Bhushan (1998a),
respectively.

PTR is possibly a function of thin-film structure, interface compliance, and size of
particles generated at the interface. A thorough understanding of PTR growth
mechanisms and the effect of operating conditions do not exist.

1.2 Use of Diamond-Like Carbon Coatings and Coating Durability (Wear and
Corrosion)

Ultra-thin DLC coatings are a possible solution to the problem of micro/nanoscale
multiphase wear. DLC coatings are mostly metastable amorphous materials that do have
some crystalline arrangement on the micro- or nanoscale. The coatings consist of random
networks of covalently bonded carbon in tetragonal (as in diamond) and trigonal (as in
graphite) local coordination. Some of the bonds are terminated by hydrogen. For ion-
beam deposited coatings, the material is 30-40 atomic per cent hydrogen. These coatings
generally reproduce substrate topography and require no surface finishing (Bhushan,
1999a).

DLC has shown encouraging micro/nanoscale mechanical and tribological
properties (Gupta and Bhushan, 1995; Li and Bhushan, 1999a; Bhushan, 1999a). The
wear life of ME tape has been shown to slightly improve with the addition of a DLC
coating (Patton and Bhushan, 1998). Mechanical durability of head sliders have been
shown to benefit from the addition of thin coatings in functional hard disk drive
(Ganapathi and Riener, 1995; Theunissen, 1998) and tape drive (Bhushan and Gupta,
1995; Bhushan et al., 1996) tests. A 20 nm thick DLC has also been shown to mitigate the problem of PTR in tape heads (Bhushan et al., 1996). It has also been shown to reduce PTR in disk heads (Xu and Bhushan, 1998b). The deposition of DLC on the surface gives all phases the same surface material properties and reduces the problem of PTR.

They have been used with some success in the corrosion-resistance of hard disks (Bhushan, 1996). Some work has been published on corrosion of magnetic thin films used for heads. In general, microscopic analysis has been used to study corrosion products on these thin films. One of the most studied is permalloy (Ni$_{0.8}$Fe$_{0.2}$) film. Oxide layers, primarily antiferromagnetic $\alpha$-Fe$_2$O$_3$, are found to form on the surface of permalloy films (Bajorek et al., 1971; Lee and Eldridge, 1977). These oxide layers can improve the atmospheric corrosion resistance of the films. The layers’ ability to improve corrosion resistance is dependent on the deposition parameters of the permalloy films and on postoxidation treatment (Lee et al., 1979). The products that do form on the surface consist of metal from the surface and of elements from the pollutant gases. Corrosion of another magnetic thin film, Fe-N, can be reduced by the addition of nitrogen, oxygen, or copper (Katori et al., 1994).

Much work has also been published on metallic magnetic tape corrosion. When the magnetic tape industry moved away from the oxide particulate tapes $\gamma$-Fe$_2$O$_3$ and CrO$_2$, whose particles are chemically inert (Speliotis, 1990), and towards MP tape, problems were found with corrosion stability (Speliotis, 1990; Yamamoto et al., 1990; Mathur et al., 1991). It was then shown that the iron particles in MP tape could be stabilized, thereby making a more corrosion-resistant tape, by forming a thin oxide layer.
on the surface (Yamamoto et al., 1990), by choosing an appropriate binder (Mathur et al., 1992), or by choosing an appropriate iron particle size (Perettie and Speliotis, 1994). In other studies (Djalali et al., 1991; Okazaki et al., 1992; Sides et al., 1994; Anoikin et al., 1996), the corrosion stability of MP tape has been reported to be at least fair (in some cases excellent), giving good enough stability for most applications. ME tape has not shown good corrosion stability (Speliotis and Peter, 1991; Kampf et al., 1995; Anoikin et al., 1996). The fact that the magnetic layer of ME tape, which is a Co-Ni thin-film evaporated onto a polymer substrate, is composed entirely of metal, should make it more susceptible to corrosion than a particulate tape, like MP, which has a magnetic layer composed largely of a polymer binder. Nothing has been published on corrosion of DLC coated ME tape.

The researchers cited above used temperature & humidity (T & H) and/or multi-component flowing mixed gas tests, such as Battelle Class II (BC II) tests (Abbott, 1987, 1990), to perform corrosion experiments. Instead of examining the corrosion products themselves, almost all of the above tape corrosion researchers measured their effects indirectly. They measured changes in magnetization and coercivity (which does not change much) and changes in signal amplitude and dropouts. Those who did examine corrosion products (Anoikin et al., 1996) found that corrosion in tapes is a localized phenomenon and is most strongly affected by Cl₂ gas (in multi-component flowing mixed gas tests).
1.3 Macro- and Micro/Nanoscale Two-Body Abrasive and Adhesive Wear of Ceramics and Metals

The mechanisms of head substrate (which can be either ceramic or metal) wear, with sliding against MP tape, have been shown to be a combination of abrasive and adhesive wear (Bhushan, 1996). In abrasive wear material is removed from a surface by a hard or a very rough surface, by ploughing or cutting (Bhushan and Gupta, 1997). For metals, which deform plastically, the volume of material removed by abrasive wear is commonly modeled as,

\[ V = \frac{kWL}{H} \]  

(1.2)

where \( V \) is the volume of worn material, \( k \) is a constant that depends on asperity geometry and the fraction of displaced material actually removed, \( W \) is the normal load, \( L \) is the sliding distance, and \( H \) is the hardness of the worn surface. The validity of this model for metals has been verified experimentally (Khruschov, 1957; Avient et al., 1960; Khruschov, 1974; Larsen-Basse, 1991). Rabinowicz (1983) has studied the hardness of abrasives relative to the hardness of the worn surface, and its effect of wear. Wear drops off markedly when the worn surface hardness is more than ~80% of the abrasive surface hardness. A number of authors have studied the effect of abrasive size and grain size (Kehr et al., 1975; Moore and Swanson, 1983; Forrest et al., 1993). Larger abrasives and smaller worn surface grains lead to higher wear.

Eq. (1.2) has been found not to be valid for ceramics in general. Since the predominant mode of fracture for ceramics is brittle rather than plastic, fracture
toughness turns out to have an important role in wear. Evans and Marshall (1981) derived an expression for volume of wear for ceramics under abrasive wear,

\[ V = aNL \frac{(E/H)w^{9/8}}{K_c^{1/2}H^{5/8}}, \]  

(1.3)

where \( V, L, \) and \( H \) are the same as in Eq. (1.2), \( \alpha \) is a material-independent constant, \( N \) is the number of particles in contact, \( E \) is Young’s modulus, \( w \) is the load per particle, and \( K_c \) is mode I fracture toughness of the worn surface. This equation and similar ones have been verified experimentally on the macro-scale (Evans and Marshall, 1981; Moore and King, 1980).

This model for ceramic wear takes extension of lateral cracks to be the material removal mechanism. Such macroscopic fracture is unlikely at the low loads encountered at the head-tape interface (Fischer, 1998). Wear on the sub-grain scale is more likely. Such wear has not been modeled mathematically. However, authors have used Eq. (1.2) on the micro/nanoscale with metals and ceramics, where the test loads are on the same order as those found in tape drives (Andersen et al., 1997; Rutherford and Hutchings, 1997).

Interfacial adhesive junctions that form when materials are in contact initiate adhesive wear (Bhushan and Gupta, 1997). For this mode, Archard’s equation is most often used (Archard, 1953). This equation has exactly the same form as Eq. (1.2). The only difference is the interpretation of the constant \( k \). In Archard’s equation this is called the wear coefficient and is a measure of the probability of a wear particle being generated.
at particular asperity contacts. Archard’s equation has been used with metals and ceramics. No distinction is made between the macro- and micro/nanoscales in the literature.

1.4 Three-Body Abrasive Wear of Ceramics and Metals

As stated earlier, the wear of the thin-film of tape heads is believed to be caused by three-body abrasion. Two-body abrasion was discussed in the previous section. In two–body abrasion, the abrasive remains fixed to the abrading surface. In three-body abrasion, the abrasive is loose, trapped between the two surfaces. The difference is illustrated in Figure 1.3. Rabinowicz et al. (1961) showed that three-body abrasion of metals follows Eq. (1.2), but the constant k is about one order of magnitude lower than in the case of two-body abrasion. The fact that the third-body is rolling, rather than sliding, during much of the contact would seem to explain this behavior. Research has also been conducted on three-body abrasion of ceramics. Some have found equations involving fracture toughness, like Eq. (1.3), to be good models (Buijs and Korpel-van Houten, 1993; Yamamoto et al., 1994). Xie and Bhushan (1996) derived an expression involving hardness, particle radius, Young’s modulus, and particle distribution. These expressions also apply generally to macroscale events.

1.5 Macroscale Wear of Multiphase Materials

Various authors have studied wear of multiphase materials on the macro-scale (Khruschov, 1974; Garrison, 1982; Axén and Jacobson, 1994; and Axén and Hutchings, 1996). Khruschov (1974) found that the relative wear resistance of a multiphase material
is equal to the sum of the products of the areal fraction of the separate constituents multiplied by the constituent’s individual relative wear resistance. This relation is similar in shape to the rule of mixtures relations used to calculate overall mechanical properties of composites, such as the elastic modulus. Khruschov (1974) conducted wear tests on various samples of multiphase materials to relate abrasive wear to material properties. Results show an extremely good correlation between the experimental and predicted results. Khruschov (1974) states that the relation only works with ductile materials. For brittle or porous materials, abrasive grains enter the pores and the wear resistance of the material drops. Garrison (1982) also shows that Khruschov’s expression does not accurately predict wear resistance of materials with a brittle phase (metal – ceramic composites).

Axén and Jacobson (1994) derived a more complex model of multiphase wear. They find that behavior can vary from that predicted by Khruschov. Khruschov’s
relation assumes that all phases wear at an equal rate. This implies that the most efficient possible pressure distribution over the phases is experienced. This does not always occur. A less efficient pressure distribution causes differential wear, which can lead to large reinforcement pullouts in composites as the matrix is worn at a higher rate and its support of reinforcements is lost.

1.6 Objectives of Research

The overall objective of this research is to achieve a thorough understanding of micro/nanoscale differential wear of a multiphase material in a particular application: head wear in magnetic tape drives. Mechanisms of such wear are not well understood. The research culminates in an analytical model of PTR. The model’s predictions are checked against experimental results.

The use of ultra-thin DLC coatings in the prevention of micro/nanoscale differential wear and in corrosion resistance is another objective. The use of these coatings also give insight into the overall question of differential wear.

1.7 Organization of Dissertation

Two problems are addressed in this dissertation: micro/nanoscale differential wear and corrosion. Common introductory (Chapter 1), experimental methodology (Chapter 2), and concluding (Chapter 5) chapters are used for the two topics. Since the two topics are independent, results, analysis, and discussion for the two are placed in separate chapters: Chapter 3 for micro/nanoscale differential wear and Chapter 4 for corrosion.
CHAPTER 2

EXPERIMENTAL METHODOLOGY AND SPECIMENS

2.1 Differential Wear (PTR) and Loose Particles

2.1.1 Drive Test Apparatus and Procedures

All drive tests were conducted in a class 10,000 laboratory environment (22±1 °C and 45±5 % RH) using one of the commercial linear tape drives shown in Figure 2.1. Most of the drive tests were conducted with the Honeywell 96 tape drive shown in Figure 2.1(a). In this drive a vacuum pump and column are used to control tape tension. A head is mounted on a linear stage that is used to change the head wrap. Four strain gages fixed to the head mount and wired into a Wheatstone bridge circuit are used to measure friction force. A chart recorder is used to record the amplified signal. The coefficient of friction calculation for this transducer and head-tape arrangement is outlined in Appendix A.

One test was carried out using the Bell & Howell VR-3700B tape drive shown in Figure 2.1(b). In this drive, spring loaded tension arms are used to control tension. This drive has been observed to produce more loose tape contamination particles than the Honeywell 96. This is probably a result of the fact that the tape encounters more tape path materials in the Bell & Howell. A few tests were conducted using an Advanced Research Corporation (ARC) model 20 linear tape drive; a schematic for this is shown in
Figure 2.1: (a) Schematics of the Honeywell 96 linear tape drive, (b) the Bell & Howell VR-3700B linear tape drive, and (c) the ARC model 20 linear tape drive
Figure 2.1 continued

(b) continued on next page
Figure 2.1 continued

(c) Stationary guides with strain gages
Stationary guides
Tape reels

Figure 2.1(c). To control tension in the ARC model 20, the take-up reel turns slightly faster than the supply reel. In this drive, tension is found using strain gages that measure the deflection of two stationary guides in the tape path (Hunter and Bhushan, 2001). For all drives, a head is mounted on a linear stage that penetrates into the tape path and controls head wrap.

For each test, a head was placed in the mount and lowered into the tape, fully wrapping the tape over the head. The head was always placed in the mount in the same direction so that the same poles were imaged (when measuring PTR) with the stand alone atomic force microscope (SAAFM) each time. For the tests conducted in the Honeywell 96 and Bell & Howell tape drives, a 600-m length of tape was run back and forth over the head and is stopped periodically to measure PTR. For all but one of the tests with uncoated heads, exactly one length of 600-m tape was used for the entire test. For each test conducted in the ARC model 20 drive, a single 130-m length of tape was used. For tests with DLC coated heads, a new length of tape was placed in the drive (and the previous length was put aside) at various points during drive testing. This was performed to reduce the effect of tape burnishing on PTR. The tape was first replaced after 500 km and was then replaced at intervals of 200 to 350 km (when the head is removed from the drive for a PTR measurement) until the test was terminated. From one experiment to another, tape tension and tape speed were varied. Tape tensions vary between 0.8-2.2 N, and tape speeds vary between 1.5-4.0 m/s.
PTR and overcoat recession (recession of the $\text{Al}_2\text{O}_3$ thin-film overcoat that makes up part of the head’s thin-film structure) were measured using the SAAFM. All of the specimens were examined using optical microscopy. Auger electron spectroscopy (AES) was used for chemical analysis of one of the coated heads.

2.1.2 Magnetic Head and Tape Specimens for Drive Tests

Dummy thin-film $\text{Al}_2\text{O}_3$-TiC and Ni-Zn ferrite heads were used in all differential wear and particle contamination tests. While a working head uses an inductive write module glued to a magnetoresistive read module, the heads used here consist of two inductive write modules glued together. Four types of heads were used: two-module with blind slots (entire head is 8 mm wide and 19 mm long, with a 20 mm radius), two-module with transverse slots (entire head is 8 mm wide and 19 mm long, with a 20 mm radius), three-module with transverse slots (entire head is 7 mm wide and 21 mm long, with a 10 mm radius), and single-module (entire head is 4 mm wide and 19 mm long, with a 12 mm radius). Drawings for these heads are shown in Figure 2.2. Some of the two-module heads use blind slots (slots in the direction of tape travel) to bleed out air between the head and tape to reduce the thickness of the air film (required for higher storage density). Some of the two- and all of the three-module heads use transverse slots (slots in the direction transverse to tape travel) to bleed out air. The two-module blind- and transverse-slotted heads have similar thin-film structures. These two heads’ overall contours, aside from their slot geometry, are the same. The single-module heads use no slots. The thin-film geometry for all heads is detailed in Table 2.1 and Figure 2.2. Each of the two-module heads, shown in Figure 2.2(a) and 2.2(b), has eighteen channels, i.e.
### Table 2.1: Details of test samples and test plan for differential wear tests

<table>
<thead>
<tr>
<th>Substrate material</th>
<th>RF-sputtered undercoat and material</th>
<th>Pole thickness and material</th>
<th>RF-sputtered overcoat and material</th>
<th>Tape</th>
<th>Tape Drive</th>
<th>Speed (m/s)</th>
<th>Sliding distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Two-module blind-slotted head tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al₂O₃-TiC</td>
<td>2 µm Al₂O₃</td>
<td>5 µm CZT</td>
<td>22 µm Al₂O₃</td>
<td>A</td>
<td>Honeywell 96</td>
<td>1.5 / 2.2</td>
<td>500</td>
</tr>
<tr>
<td>Al₂O₃-TiC</td>
<td>2 µm Al₂O₃</td>
<td>5 µm CZT</td>
<td>22 µm Al₂O₃</td>
<td>A</td>
<td>Honeywell 96</td>
<td>3.0 / 2.2</td>
<td>278</td>
</tr>
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<td>5 µm CZT</td>
<td>22 µm Al₂O₃</td>
<td>A</td>
<td>Honeywell 96</td>
<td>1.5 / 0.8</td>
<td>500</td>
</tr>
<tr>
<td>Al₂O₃-TiC</td>
<td>2 µm Al₂O₃</td>
<td>5 µm CZT</td>
<td>22 µm Al₂O₃</td>
<td>A</td>
<td>Bell &amp; Howell</td>
<td>1.5 / 2.2</td>
<td>500</td>
</tr>
<tr>
<td>Ni-Zn ferrite</td>
<td>None</td>
<td>0.1 µm &amp; 5 µm Ni-Fe</td>
<td>27 µm Al₂O₃</td>
<td>A</td>
<td>Honeywell 96</td>
<td>1.5 / 2.2</td>
<td>1000</td>
</tr>
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<td><strong>Two-module transverse-slotted head tests</strong></td>
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<td>5 µm CZT</td>
<td>17 µm Al₂O₃</td>
<td>A</td>
<td>Honeywell 96</td>
<td>1.5 / 2.2</td>
<td>415</td>
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<td>5 µm CZT</td>
<td>17 µm Al₂O₃</td>
<td>A</td>
<td>Honeywell 96</td>
<td>1.5 / 2.2</td>
<td>750</td>
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<td>5 µm CZT</td>
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<td>A</td>
<td>Honeywell 96</td>
<td>1.5 / 2.2</td>
<td>2000</td>
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<tr>
<td>Ni-Zn ferrite</td>
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<td>1 µm &amp; 5 µm CZT</td>
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<td>1000</td>
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<td>None</td>
<td>40 µm Al₂O₃</td>
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<td>1st tape length - 500 &amp; 2nd tape length -500</td>
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<td>None</td>
<td>40 µm Al₂O₃</td>
<td>B</td>
<td>Honeywell 96</td>
<td>1.5 / 2.2</td>
<td>500</td>
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<td>None</td>
<td>9 µm Al₂O₃</td>
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<td>Honeywell 96</td>
<td>1.5 / 2.2</td>
<td>500</td>
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<tr>
<td>Al₂O₃-TiC</td>
<td>None</td>
<td>None</td>
<td>3 µm Al₂O₃</td>
<td>A</td>
<td>Honeywell 96</td>
<td>1.5 / 2.2</td>
<td>500</td>
</tr>
<tr>
<td>Al₂O₃-TiC</td>
<td>None</td>
<td>5 µm CZT</td>
<td>None</td>
<td>A</td>
<td>Honeywell 96</td>
<td>1.5 / 2.2</td>
<td>500</td>
</tr>
<tr>
<td>Ni-Zn ferrite</td>
<td>None</td>
<td>None</td>
<td>10 µm Al₂O₃</td>
<td>A</td>
<td>Honeywell 96</td>
<td>1.5 / 2.2</td>
<td>500</td>
</tr>
<tr>
<td><strong>Single-module head tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al₂O₃-TiC</td>
<td>6 µm Al₂O₃</td>
<td>4 µm CZT</td>
<td>18 µm Al₂O₃</td>
<td>B</td>
<td>ARC model 20</td>
<td>4.0 / 1.0</td>
<td>1000</td>
</tr>
<tr>
<td>Al₂O₃-TiC</td>
<td>6 µm Al₂O₃</td>
<td>4 µm CZT</td>
<td>2.5 µm Al₂O₃</td>
<td>B</td>
<td>ARC model 20</td>
<td>4.0 / 1.0</td>
<td>1000</td>
</tr>
<tr>
<td>Al₂O₃-TiC</td>
<td>5 µm Al₂O₃</td>
<td>4 µm FeAlN</td>
<td>21 µm Al₂O₃</td>
<td>B</td>
<td>ARC model 20</td>
<td>4.0 / 1.0</td>
<td>1000</td>
</tr>
<tr>
<td><strong>Coated head wear tests</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>10 nm coated</td>
<td>2 µm Al₂O₃</td>
<td>5 µm Ni-Fe</td>
<td>22 µm Al₂O₃</td>
<td>A</td>
<td>Honeywell 96</td>
<td>1.5 / 2.2</td>
<td>4200</td>
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<tr>
<td><strong>Two-module blind-slotted head tests</strong></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>5 nm coated</td>
<td>2 µm Al₂O₃</td>
<td>5 µm CZT</td>
<td>17 µm Al₂O₃</td>
<td>A</td>
<td>Honeywell 96</td>
<td>1.5 / 2.2</td>
<td>3600</td>
</tr>
<tr>
<td>10 nm coated</td>
<td>2 µm Al₂O₃</td>
<td>5 µm CZT</td>
<td>17 µm Al₂O₃</td>
<td>A</td>
<td>Honeywell 96</td>
<td>1.5 / 2.2</td>
<td>3800</td>
</tr>
<tr>
<td>20 nm coated</td>
<td>2 µm Al₂O₃</td>
<td>5 µm CZT</td>
<td>17 µm Al₂O₃</td>
<td>A</td>
<td>Honeywell 96</td>
<td>1.5 / 2.2</td>
<td>4150</td>
</tr>
</tbody>
</table>
Figure 2.2: (a) Schematics of two-module blind-slotted heads, (b) two-module transverse-slotted heads, (c) three-module transverse-slotted heads, and (d) single-module heads
Figure 2.2 continued

(c) Al₂O₃-TiC or Ni-Zn ferrite
Thin film
Slot

Thin-film structure
Al₂O₃-TiC or Ni-Zn ferrite
x µm Al₂O₃ or CZT
x = 3, 5, 9, 10, 40

(d) Al₂O₃-TiC
Al₂O₃

Thin-film structure
Al₂O₃-TiC
x µm Al₂O₃  x = 2.5, 20
4 µm CZT or FeAlN
1 µm Al₂O₃
4 µm CZT or FeAlN
6 µm Al₂O₃

~300 µm
eighteen pole pairs; the pole material is either Radio frequency (RF)-sputtered Co-Zr-Ta (CZT) or electroplated Ni-Fe and the supporting thin-films are RF-sputtered Al$_2$O$_3$. Al$_2$O$_3$-TiC and Ni-Zn ferrite are used as substrate materials to study the differences in PTR due to these materials. These heads are also used for particle contamination tests. Each of the three-module heads, shown in Figure 2.2(c), has a single thin-film material from end to end. Substrate materials are also varied here to study their influence on recession. The thin-film materials, either RF-sputtered CZT or RF-sputtered Al$_2$O$_3$, are varied to study their effect on recession. For these heads various thin-film thickness values are used to study the effect of thickness on recession. Each of the single-module heads, shown in Figure 2.2(d), has either RF-sputtered CZT or FeAlN poles, and RF-sputtered Al$_2$O$_3$ supporting thin-films. For these heads, the pole material and thickness of the overcoat material (one of the supporting films, as shown in Figure 1.1) are varied to study their influences on PTR. The root mean square (RMS) roughness of the heads, as measured with an AFM with a scan size of 10 µm x 10 µm, is 2.5 nm.

One of the two-module blind-slotted heads received a 10 nm thick ion-beam DLC coating. Ion-beam DLC coatings of 5 nm, 10 nm, and 20 nm thickness were deposited on three of the two-module transverse-slotted heads by a commercial vendor. In the direct ion beam deposition technique, the coating is deposited with an accelerated carbon ion beam. The sample is precleaned by ion etching and then a 2-3 nm thick amorphous silicon adhesion layer is deposited by ion beam sputtering. An ionized methane (which is used as the carbon source) beam is then deposited on the substrate (Bhushan, 1999a). Table 2.1 shows a complete list of the tests that were run.
In order to measure the wear of the head substrates Al$_2$O$_3$-TiC and Ni-Zn ferrite, a commercial nanoindenter was used to create scratches in the surfaces of two two-module transverse-slotted heads. These scratches are used as fiducial marks; measurement of the change in the distance between the top surface and the scratch is a measurement of the wear of the top surface (Bhushan and Lowry, 1995). To make the scratches, a conical tip with a radius of 1 µm and an included angle of 60° was mounted to the nanoindenter. Scratches were made in constant depth mode with a normal load of 6 mN for Al$_2$O$_3$-TiC and 2 mN for Ni-Zn ferrite. After scratching, the heads were ultrasonically cleaned in a flask of methanol to clean away the debris created by the scratch.

A double-layer MP tape, MP tape A (substrate/total thickness = 10.9/14.4 µm and with an RMS roughness of 11.1 nm) or a single-layer MP tape, MP tape B (substrate/total thickness = 6.5/9 µm and an RMS roughness of 9.3 nm) are used in all tests. Figure 2.3 shows a schematic of the double-layer tape. The magnetic layer of this tape consists of iron and cobalt magnetic particles, which have a needle-like shape and an approximate size of 100 nm x 20 nm (Ejiri, 1999). It also consists of HCAs of alumina, which are spherical and have an average particle diameter of between 200 and 300 nm (Ejiri, 1999). Sample AFM maps for the two tapes are shown in Figure 2.4. The abbreviation “P-V” used in Figure 2.4 stands for peak-to-valley distance and is defined as the distance between the highest peak and deepest valley. The tape used for each test is indicated in Table 2.1.

The two-module blind-slotted heads were generally used more than once. After a test, the head was restored to like-new condition using a refurbishing process. A head is refurbished by tape lapping with a diamond lapping tape with a substrate thickness of 75
μm. Two tapes, one with a grit size of 1.0 μm and one with a grit size of 0.5 μm, are run across the head surface. In the tape lapping process, the tensioned lapping tape is wrapped over the head in a manner similar to that of a recording tape and is moved relative to the head in a reciprocating motion. The PTR of the worn head is reduced with this process. Each head was refurbished before it was used in another test. The head roughness after refurbishing was found to be close to that of a new head.

Figure 2.3: Cross-sectional view of double-layer MP tape (MP tape A) used in drive tests

2.1.3 Differential Wear Measurement

2.1.3.1 AFM Measurement Procedure

The two-module heads have individual pole sites, where the poles are approximately 90 μm long. For these tests, the same four pole pairs were measured each time the test was stopped. These four measurement sites are approximately 2.6 mm apart. For tests with the three- and single-module heads, four measurements were made at locations 2.0 mm apart each time the test was stopped. For these tests, a sample fixture and a linear stage were used to make sure that the same location was being imaged each
Figure 2.4: Three-dimensional AFM maps and roughness data for MP tapes A and B
time. For the heads that have two thin-film poles (two- and single-module heads), PTR is not generally equal for the two poles. For these cases, the reported PTR at a single site is the value for the more deeply recessed pole. For the heads with the single thin-film material (three-module heads), the recession is not generally equal over the thickness of the film. For these cases, the reported recession is measured at the center of the region. The variation of these four site measurements from the reported average is usually fairly small, generally less than ten nanometers. The measurement error associated with these measurements is much lower. The height resolution of the AFM is a fraction of a nanometer and errors associated with data post-processing are minimized by manually leveling the AFM with respect to the sample before data is acquired.

SAAF M scans are taken of the thin film region of the tape heads to measure the recession at various points during the course of drive tests. The operation of the SAAF M is quite similar to the operation of other AFMs. A description of the operation of the SAAF M is given in Appendix B. The major advantage of the SAAF M is that the operator can vary the pitch and roll angles of the tip, which allows for manual leveling of the tip with respect to the sample. If this were not possible the operator would have to rely completely on software corrections, which may introduce errors, particularly for samples with small radii. This manual correction procedure is described here.

Great care must be taken in obtaining raw data from the SAAF M. The fact that the tape head sample has a rather small radius (10, 12, or 20 mm) and that the scan size is so large (100 x 100 µm) makes obtaining good raw data critical. In order to measure recession, a tape head specimen is placed face up on an X-Y stage so that the long axis of the head points toward the experimenter. A schematic of the X-Y stage is shown in
Figure 2.5. From the experimenter’s point of view, one of the head’s write modules is on the left and the other is on the right for the two-module heads. For the three- and single-module heads, the write-module is in the center of the head. An SAAFM is placed on a flat platform suspended just above the tape head specimen. With the aid of a low magnification optical microscope, the tip of the SAAFM is moved (using the engagement screws, which raise and lower the entire SAAFM) downward until it comes close to the head surface. Using the X-Y stage, the head is moved left or right until the thin film structure of the right module (for two-module heads) or the center module (for three- and single-module heads) is just beneath the SAAFM tip. With the use of a strong light source, the poles in the thin film region can be seen with the optical microscope. For the two- and single-module heads, the head is moved back, away from the experimenter (using the X-Y stage), until the first pole is in view. For the three-module heads, the head is moved to the proper position with the aid of the stage micrometer. The site to be imaged is found relative to the first site. Moving the tape head forward, the first site is found and is moved into the same focal plane as the SAAFM tip. In order to image a pole tip, the SAAFM tip is brought down onto the tape head surface so that the tip is approximately normal to the head at its apex, which is located at the thin film region. For the two-module heads, the thin film region is not located at the top of the face, but is positioned at an angle of approximately 10-20 degrees with the horizontal axis. So the SAAFM must be positioned at this angle, in one plane, to obtain a proper image. Figure 2.6 shows the position of the SAAFM with respect to the sample and the X-Y stage. For the three- and single-module heads, the thin film is located at the top of the face and the SAAFM is positioned at 0 degrees with the horizontal axis. The SAAFM’s fast scan
Figure 2.5: Schematic of X-Y stage used for recession measurement
Figure 2.6: Schematic showing position of SAAFM with respect to the sample and X-Y stage during engagement for two-module heads
direction (explained in Appendix B) is set to the direction perpendicular to the long axis of the thin-film region (left to right from the experimenter’s point of view). A scan rate of 1 Hz is used and 256 data points are collected along each of the 256 scan lines. The image size is set to 100 x 100 µm so as to image entire pole tips.

After engagement, while in the midst of scanning, the raw data are examined in the fast and slow scan directions. If a significant slope exists in one or both directions, the SAAFM tip must be withdrawn and the orientation of the tip with respect to the sample must be changed (by adjusting the engagement screws) so as to remove the slope. The tip is then engaged again. Several of these adjustments are generally required to sufficiently remove slope. The thin film region should also be kept in about the center of the scanned image (with the X-Y stage) while making the adjustments. At this point it is generally necessary to move the head forward or backward to get the entire pole tip into the image. After this is accomplished, an image may be captured to a file. This procedure is then repeated for three more measurements along the same tape head module. If care is not taken in performing the measurement, significant errors may occur. After some post-processing, which is discussed in the next section, the recession of the average 2-D profile is taken for each measurement with the aid of the SAAFM software. The average of these four values is reported as the recession at the test condition and sliding distance.

2.1.3.2 Post-Processing of Raw AFM Data

A raw SAAFM image of a pole tip is shown in Figure 2.7(a). At most, two operations are performed on raw data. First, a zero-order Flatten is applied. The Flatten
Figure 2.7: (a) Raw SAAFM image of a pole tip, (b) image of a pole tip after zero-order Flatten operation, and (c) image of a pole tip after zero-order Flatten and first-order Planefit operations.
operation is used to eliminate image bow in the slow scan direction (caused by physical bow in the SAAFM instrument itself), slope in the slow scan direction, and bands in the image (caused by differences in scan height, due to debris, etc., from one scan line to the next). The Flatten operation takes each scan line and subtracts the average value of the height along each scan line from each point in that scan line (Anon., 1993). This brings each scan line to the same height, without affecting the recession measurement. Figure 2.7(b) is the image of the raw data with a Flatten operation applied. Notice in Figure 2.7 that the scan lines are perpendicular to the long axis of the thin film region. So, subtracting the same value from each point on the line does not result in any difference in height between any two points on that line. Therefore, this operation cannot cause any change in the recession measurement. If the scan lines were parallel to the long axis of the thin film region, this Flatten operation would eliminate recession altogether. So, the scan should always be taken so that the fast scan direction is perpendicular to the long axis of the thin-film region.

Next, a first- or second-order Planefit is applied in the fast scan direction. The Planefit operation is used to eliminate bow and slope in the fast scan direction. The Planefit operation calculates a best fit plane for the image and subtracts it from the image. This plane has a constant, non-zero (generally) slope in the fast scan direction and zero slope in the slow scan direction for a first-order Planefit (Anon., 1993). Figure 2.7(c) is the image with a Flatten operation and a first-order Planefit operation applied. A higher order polynomial “plane” could be used, but it was decided to keep the curvature that actually exists in the head for this data. For much of the data reported in Chapter 3, a second-order Planefit was used to remove the head contour radius so that the recession
could be measured more accurately for heads with a low recession and/or a small head contour radius. As long as sufficient care is taken in obtaining the raw data, the Planefit operation, whether it is first- or second-order, should not affect the recession measurement greatly. Depending upon the quality of the raw data, the Flatten operation and/or the Planefit operation may not be required at all. Notice in Figure 2.7 that the average 2-dimensional profiles for the raw data and for the processed data are not much different.

2.1.4 Contamination Measurement

2.1.4.1 Optical Microscopy Measurement of Loose Particles Found on Head

To measure loose particle generation, which has an effect on differential wear, a number of tests were conducted, as shown in Table 2.2. All drive tests were conducted with the Honeywell 96 (shown in Figure 2.1(a)) using 600-m segments of MP tape A and the drive methodology described in section 2.1.1. The head specimens used for these tests and the total sliding distance for each test is given in Table 2.2. Two procedures were used: (1) one in which optical micrographs were taken of the particles found on a head surface following a drive test, and (2) one in which particles were extracted from the head using a solvent and examined following a drive test. The first procedure gives information about the total amounts of debris and its distribution on the head surface. The second measurement allows for the examination of individual particles for size, shape, and chemical information.

In the first procedure, optical micrographs were taken of tape debris deposited on the head surface at 100x and 200x magnification. In order to quantify the various types
Table 2.2: Details of test samples and test plan for particle contamination tests

<table>
<thead>
<tr>
<th>Substrate material</th>
<th>Type of test</th>
<th>Tape</th>
<th>Tape Drive</th>
<th>Speed (m/s)/tension (N)</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Head surface optical microscopy tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two-module blind-slotted head tests</td>
<td>Al₂O₃-TiC Drive test for 100 km of sliding</td>
<td>A</td>
<td>Honeywell 96</td>
<td>1.5 / 2.2</td>
<td>Head surface microscopy</td>
</tr>
<tr>
<td>Two-module transverse-slotted head tests</td>
<td>Al₂O₃-TiC Drive test for 100 km of sliding</td>
<td>A</td>
<td>Honeywell 96</td>
<td>1.5 / 2.2</td>
<td>Head surface microscopy</td>
</tr>
<tr>
<td>Solvent particle-extraction and laser particle counter tests</td>
<td>Al₂O₃-TiC Drive test for one hour, 5.5 km of sliding</td>
<td>A</td>
<td>Honeywell 96</td>
<td>1.5 / 2.2</td>
<td>Solvent extraction</td>
</tr>
<tr>
<td>Ni-Zn ferrite</td>
<td>Drive test for one hour, 5.5 km of sliding</td>
<td>A</td>
<td>Honeywell 96</td>
<td>1.5 / 2.2</td>
<td>Solvent extraction and laser particle counter</td>
</tr>
<tr>
<td>Ni-Zn ferrite</td>
<td>Exposure to drive environment for one hour</td>
<td>-</td>
<td>Honeywell 96</td>
<td>-</td>
<td>Solvent extraction</td>
</tr>
<tr>
<td>Ni-Zn ferrite &quot;Clean&quot; head, i.e. no drive test, no exposure</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Solvent extraction</td>
</tr>
</tbody>
</table>

of debris, computerized image analysis was performed on these optical micrographs. First, each micrograph was scanned into a computer at 75 dots per inch as a grayscale image using a flatbed scanner. Any particle longer than 3.4 µm, for the micrographs taken at 100x, and 1.7 µm, for the micrographs taken at 200x, can be resolved. An image file (each file corresponds to a single micrograph) was processed using an image analysis program. The image was processed appropriately to eliminate any dark features that were not debris particles. These dark features, which include the line along which the write modules are glued together and tool marks within the bleed slots, are not difficult to distinguish visually and can simply be erased using the software. Then a grayscale darkness threshold was applied to the image. Debris particles show up as the dark portions in the threshold images. Sample threshold images, with their corresponding
optical micrographs, are shown in Figure 2.8. After the scale of the micrograph was defined in the image analysis program, the surface area of each threshold particle or agglomerate was calculated. These data were used to find the total area of debris. This surface area data was then used to quantify the debris found on the head. The surface areas of the debris found in the micrographs taken for a test were summed. This gave the total amount of debris found on a head. The resolution of this technique is estimated to be approximately \( \pm 0.05 \text{ mm}^2 \) for the total amount of debris found on a head (Scott and Bhushan, 1999a).

A number of solvent particle-extraction tests were conducted; these are listed in Table 2.2. Before each test the head sample was washed out in a clean flask filled with methylene chloride, the solvent used for extraction. It was then allowed to dry under a class 100 laminar flow hood for five hours.

For two tests, a cleaned head was run against MP tape A for one hour, or 5.5 km. The head was then removed from the drive and washed out in a clean flask filled with methylene chloride. This wash was poured through a filtration setup (Bhushan et al., 1999). This filtration setup is shown in Figure 2.9. The used solvent was collected in a vacuum flask; it was forced through the setup using pressure applied by a syringe. The twelve millimeter diameter polycarbonate filters (catalog no. FHLP01300, Millipore Inc., Danvers, MA) used in the setup have a pore size of 0.5 \( \mu \text{m} \). During filtration, the filter was placed inside a spot sampler (product no. 54315, E.F. Fullam Inc., Latham, NY), a device used to concentrate particles onto a small area near the center of the filter for ease
Figure 2.8: Optical micrographs and threshold images used to measure contamination particles
Figure 2.9: Particle filtration setup (taken from Bhushan et al., 1999)
of identification. After all of the wash was filtered through the setup, the filter was
removed from the spot sampler and was allowed to dry under the class 100 laminar flow
hood for five hours.

For another test, the head was placed in the Honeywell 96 drive for one hour, but
the head was not placed in contact with the tape while the drive was run, i.e. the head was
exposed to the drive environment but was not slid against the tape. This test was used to
measure the number and type of environmental particles (particles that are not generated
during contact) found on the head after exposure. Following this test, the head was
washed out and the wash was filtered, as in the other tests. For another test, the head was
neither slid against tape nor exposed to the drive environment. For this, the head was
simply washed out and the wash was filtered as before. The purpose of this test was to
measure the number and type of particles that are found on the “cleaned” head. Ideally
the number of particles would be zero.

After the filters were dried they were examined under an optical microscope. In
these measurements, optical micrographs of the particles were taken using a monochrome
CCD camera at a pixel resolution of 3.6 µm. All of the particles on each filter were
photographed. The same computerized image analysis described above for the
micrographs taken of the head surface was performed on these micrographs. After the
scale of the photograph was defined in the image analysis program, the number of
particles and the surface area of each threshold particle or agglomerate was calculated.
The software was also used to fit an ellipse to each particle to approximate the length and
width dimensions. The length of the major axis of the ellipse is reported as the length of
the particle in the data shown in Chapter 3. This data was used to quantify the individual
particles found on the head.

A few of the filters were then gold-palladium coated and examined in a scanning
electron microscope (SEM). They were also examined chemically using electron
dispersive x-ray (EDX) analysis. In EDX, an incident electron beam causes the emission
of X-rays from the sample down to a depth of approximately 1 to 2 µm. The emitted X-
rays have energies that are characteristic of the elements present near the surface.

2.1.4.2 Laser Particle Counter Measurement of Airborne Loose Particles

As shown in Table 2.2, during one of the solvent particle-extraction drive tests in
the Honeywell 96, airborne particles were counted using a laser particle counter (PMS
Inc., Boulder, CO, model no. ULPC-1001-CPC-2CH). In a laser particle counter, air to
be sampled is transported to the particle detecting optical system by the particle counter’s
air sampling system. The particle counter contains a precision He-Ne laser illuminated
optical system that allows particle sizing by collecting the scattered light from each
particle, with a photodiode detector (Bhushan and Chandra, 1999).

For the system used here the particle counter pulled particles out of the
atmosphere at a flow rate of 280 cc/min using plastic tubing with an inner diameter of 6.5
mm. The end of the tube was placed approximately 5 mm to the side of the head and 5
mm above the head-tape contact. So the end of the tube was placed just above the exit
(or entrance, depending upon which direction the tape was moving) of head-tape contact
on one side. The particle count was sampled continuously for 5 min. intervals. Data was
obtained in two different size bins: 0.1 – 0.3 µm and > 0.3 µm. An attempt was made to clean the drive environment (a volume of approximately 42,000 cc) with clean air to eliminate background particles and concentrate on those generated during sliding (Bhushan and Chandra, 1999; Chandra and Bhushan, 2000). The air was cleaned by passing it through disposable 0.2 µm PTFE membrane filters (Gelman Sciences, Ann Arbor, MI). The specification for these filters is for liquid filtration; for air the filters are capable of eliminating particles that are even smaller (Chandra and Bhushan, 2000). Two inlet clean air flows were used in the drive, both at 25,000 cc/min. These air flows were not enough to eliminate the background. The fact that the drive is not particularly well sealed and that the vacuum column used in the drive generates an extra flow in the drive probably accounts for the failure to eliminate the background. Therefore, the data that was generated and shown in Chapter 3 includes background particles.

2.1.5 Head-Tape Spacing Measurement Apparatus and Procedures

Head-tape spacing was measured in two-module blind- and transverse-slotted glass heads sliding against MP tape A using two-color interferometry. The two-module glass heads had the same radius and slot pattern, and were the same size as those used in the wear experiments. The system used was a Tape Spacing Analyzer, produced by Microphysics Inc. In the interferometry technique, light from an objective lens is directed at the glass head while it is in contact with the tape (Lacey and Talke, 1992). The light waves reflected from the interface combine and interfere with each other, causing fringe patterns whose intensity is a periodic function of spacing between head and tape. A CCD camera, mounted above the microscope objective lens is used to
capture a digital image to a personal computer. The average spacing over a 430 x 280 µm image is reported as the spacing at the given condition. The resolution of this technique is approximately ± 5 nm. Measurements were made at tape tensions of 1.1 N, 1.7 N, and 1.9 N over a tape speed range of 0 - 10 m/s.

2.2 Corrosion

2.2.1 Battelle Class II and Temperature & Humidity Tests

Battelle Class II (BC II) tests were performed at Battelle Memorial Institute, Columbus, Ohio. In these tests, the temperature and relative humidity (RH) are 30°C and 70%, respectively. The concentration, in parts per billion, of the pollutant gases H₂S, Cl₂, and NO₂ gases are 10, 10, and 200, respectively. Abbott (1987) gives some additional experimental details. These tests have been shown to adequately reproduce the corrosion kinetics, mechanisms and chemistries, in a short period of time, that would be experienced in a much longer period in a typical office environment (Abbott, 1985, 1990). For electrical contacts (mostly copper and gold) a ten day exposure has been found to be equivalent to five years in real time (Koch and Abbott, 1986; Djalali et al., 1991). However, this accelerating factor must be viewed with caution for the head and tape specimens used here. The accelerating factor was established with materials that are different than those used in magnetic storage devices. Also, the manner in which the specimens are exposed, for example, whether or not a magnetic tape is exposed in or out of a cartridge, affects the accelerating factor. In the present study, specimens were subjected to testing for various durations. The exposure time for each specimen subjected to the test is listed in Table 2.3.
Table 2.3: Specimens used in Battelle Class II and temperature & humidity (60°C & 90% RH) tests

For the temperature & humidity tests, specimens were placed in an environmental chamber which controls temperature to ± 1°C and RH to ± 5%. Tests were conducted at 60°C and 90% RH. Specimens were placed low in the chamber to avoid air currents, which are strongest near the top. Care was also taken to avoid positions in the chamber where water condensation was found to occur. Specimens were examined, approximately once a week, with an optical microscope to detect any obvious deposits or changes (in topography, for example). The exposure time for each specimen is listed in Table 2.3.
All specimens were examined using optical microscopy. Some were examined using AES (chosen for its high lateral resolution), scanning electron microscopy (SEM), and AFM.

2.2.2 Auger Electron Spectroscopy

The chemical nature of the corrosion deposits are found using AES. AES utilizes an electron beam with a small diameter, which allows for examination of very small spots on the sample. The incident electron beam ionizes atoms near the surface, resulting in the ejection of Auger electrons from the shells of the atoms in the first three to five atomic layers of the sample surface. So the emitted Auger electrons give a true measure of the surface. These Auger electrons, which have distinct energies depending on the element, are collected with an Auger detector. The number of counts detected gives a measure of the concentration of the various detected elements. (Each element has a distinct, known detection sensitivity.) Background noise is removed by differentiating the number of counts with respect to energy (dN/dE). Plots of dN/dE vs. E are used to find which elements were detected. These plots are shown Chapter 4 (one is also shown in Chapter 3).

2.2.3 Magnetic Head and Tape Specimens

Test specimens used for corrosion tests are listed in Table 2.3. Eight dummy Al$_2$O$_3$-TiC write modules were used in the corrosion studies. These modules are approximately 4 mm wide and 19 mm long and have a thin-film structure that is approximately 30 µm wide, sandwiched between two sections of bulk Al$_2$O$_3$-TiC. Along
the thin-film, 20 RF-sputtered CZT metal pairs are arranged. Each CZT segment is approximately 5 µm wide and 90 µm long. The remainder of the thin-film is composed of RF-sputtered Al₂O₃. DLC coatings were ion-beam deposited on six of these heads. Two received 5 nm, two received 10 nm, and two received 20 nm thick coatings. Two were not coated.

MP and ME (with and without DLC) tapes were exposed in two forms: (1) in short (~12 cm long) uncovered lengths (coupons) and (2) wound on a full spool inside a closed cartridge (but not inside a plastic storage box). The tape specimens are all commercial and all manufactured in recent years. The MP tape is 8 mm wide and has a substrate thickness of 9.8 µm, a total thickness of 13.2 µm, and a RMS roughness of 4.3 nm. The coated ME tape is 6.35 mm wide and has a substrate thickness of 6.0 µm, a total thickness of approximately 7.5 µm, and a RMS roughness of 4.0 nm. The thickness of the DLC on the coated ME tape is in the range of 8-15 nm. The uncoated ME tape is 8 mm wide and has a substrate thickness of 10.0 µm, a total thickness of 11.0 µm, and a RMS roughness of 4.0 nm.
CHAPTER 3

MICRO/NANOSCALE DIFFERENTIAL WEAR STUDIES IN TAPE HEADS (PTR)

3.1 Mechanism of Micro/Nanoscale Differential Wear in Tape Heads (PTR)

Clearly PTR is a result of differential wear of the various materials across the head. In order to reduce it, the wear modes of the surface materials must be known. The mechanisms of head substrate wear, with sliding against MP tapes, have been shown to be a combination of abrasive and adhesive wear (Bhushan, 1996). In abrasive wear, material is removed from a surface by a hard or a very rough surface, by ploughing or cutting. Interfacial adhesive junctions that form when materials are in contact initiate adhesive wear. The real object of interest in PTR is the wear mechanism of the thin-film region. To find this it is useful to look at the nature of the contact between the tape and the head’s recessed thin film. In a study cited in Chapter 1, Tsuchiya and Bhushan (1995) performed a real area of contact (RAC) measurement of tape loaded against a fabricated recess (a recess that was on the same order as a typical PTR) to investigate the contact. Sputtering a chromium film onto a glass slide and then etching a grid by photolithography created the fabricated recess. The grid elements were either 8 or 30 nm high and 40 µm apart; the thin-film regions in current tape heads are about 40 µm thick. This grid is shown in Figure 3.1(a). The objective was to measure, in a static test, the
RAC at the bottom of a gap, with respect to that measured in an area with no grid on the same slide. Pressures of 100 and 200 kPa (which are equal to or higher than contact pressures typically encountered in tape drives) were applied to press the tape against the grid patterns on the glass slide. An optical interference technique was then used to measure RAC (Bhushan, 1996); contact points appear as dark spots in these interference images.

RAC turns out to be much lower in the recesses. RAC was measured as functions of grid height and tape pressure. Figure 3.1(b) shows the ratio of the RAC (RAC ratio) in the recessed regions to that in the areas without grids as functions of the just-mentioned variables for two tapes: Co-$\gamma$Fe$_2$O$_3$ and MP. The Co-$\gamma$Fe$_2$O$_3$ (referred to as “Oxide” in Figure 3.1) and MP tapes have RMS roughness values of 10 nm and 6 nm, respectively. For both pressures RAC ratio decreased with an increase in grid height for both tapes. Co-$\gamma$Fe$_2$O$_3$ tape showed two to three times higher RAC ratio, indicating that the rougher Co-$\gamma$Fe$_2$O$_3$ tape fills the recessed areas more easily than MP tape. This implies that the Co-$\gamma$Fe$_2$O$_3$ tape should give higher PTR if the tape surface itself is wearing the thin-film region. The previous statement also assumes that MP tape does not cause more head wear, generally, than Co-$\gamma$Fe$_2$O$_3$ tape. Bhushan and Lowry (1995) show data to validate this assumption; in fact, they show that Co-$\gamma$Fe$_2$O$_3$ tape causes more head wear than MP tape.

Figure 3.2 shows core recess (analogous to PTR) vs. sliding distance for heads with CoNbZr, CoTaZr, and FeTaC magnetic materials, run against Co-$\gamma$Fe$_2$O$_3$ and MP tapes. MP tape leads to slightly higher recession despite the fact that RAC in the recess is much lower for MP tape. From this we may infer that the mechanism of wear does not
Figure 3.1: (a) Schematic of the two grid patterns etched on the sputtered chromium film on a glass slide and (b) RAC ratio (RAC in the grid area over RAC in the area without a grid) as a function of grid height for the MP and Co-$\gamma$-Fe$_2$O$_3$ (oxide) tapes at pressures of 100 kPa and 200 kPa (taken from Tsuchiya and Bhushan, 1995)
Figure 3.2: Core recess as a function of sliding distance for various experimental MIG heads against MP and Co-$\gamma$-Fe$_2$O$_3$ tapes in a linear Bell & Howell drive (taken from Tsuchiya and Bhushan, 1995)

Figure 3.3: Schematic summarizing the conclusion that three-body particles, and not a bending tape, causes the thin-film wear that results in PTR

Three-body abrasion caused by loose abrasive particles is the more likely mechanism
involve direct contact between the tape and the recessed region. The tape simply does not bend into the recessed region to a significant extent. Bhushan (1996) found, while conducting wear tests, that tape has a tendency to bend away from the apex of a head (where the thin-film region is located) rather than toward it, as a result of strain rate effects. The claim might be made that the recessed thin-film acts as a negative pressure cavity, creating a force that pulls the tape down. It is highly unlikely, however, that the negative pressure exerted by this extremely shallow “cavity”, with its rounded corners and sides, would exceed the 200 kPa pressure that Tsuchiya and Bhushan (1995) used. They found that 200 kPa does not result in a stationary tape bending into a recess to any significant extent. A tensioned, moving tape, which has an additional dynamic stiffness, would have an even more difficult time bending into a recess.

Since direct contact with the tape does not cause the thin-film wear, Tsuchiya and Bhushan (1995) proposed that wear particles from the thin-film region of the head are initially produced and that these particles are trapped at the interface and result in growth by three-body abrasion. These particles, of course, may also originate from the tape; HCAs from the tape are certainly hard enough to cause wear of the thin-film region. Harrison et al. (1998) and Xu and Bhushan (1998a) also proposed three-body abrasive wear modes for tape and disk heads, respectively. Data cited later in this chapter also support the theory that three-body abrasion is responsible for PTR. The propositions put forward in this section are illustrated in Figure 3.3.

Another interesting feature of PTR is shown in Figure 3.2. Recession tends to a steady-state value, the same value in fact, regardless of whether the recession starts out
high or low. Only the materials in contact, their topography, their separation, the head’s geometry, and the abrasive particles available at the interface, affect PTR.

3.2 Experimental Results for Changes in Head Materials, Thin-film Thickness, Drive Conditions, and Tape

3.2.1 Wear of Head Substrate Materials

As explained in Chapter 2, a commercial nanoindenter was used to create scratches in the surfaces of two two-module transverse-slotted Al$_2$O$_3$-TiC and Ni-Zn ferrite heads in order to measure head substrate wear. These scratches are used as fiducial marks; measurement of the change in the distance between the top surface and the scratch is a measurement of the wear of the top surface (Bhushan and Lowry, 1995). Wear of the head substrate materials vs. sliding distance is shown in Figure 3.4. Clearly Ni-Zn ferrite wears at a much higher rate than Al$_2$O$_3$-TiC. The fact that Ni-Zn ferrite has a hardness that is approximately three times lower than Al$_2$O$_3$-TiC accounts for this difference. Mechanical property and wear data for these and the thin-film materials used in the two- and three-module heads are shown in Figure 3.5. In Figure 3.5, “Co-Zr-Ta/Al$_2$O$_3$-TiC” is an RF-sputtered Co-Zr-Ta (CZT) thin film deposited on a polished Al$_2$O$_3$-TiC coupon. The thin films “Al$_2$O$_3$/Al$_2$O$_3$-TiC” and “Al$_2$O$_3$/Ni-Zn ferrite” are defined similarly. All of these thin films are 5 µm thick. Measurements of hardness, elastic modulus, and critical load (the point of initiation of damage at which the coefficient of friction increases to a high value or increases abruptly during a test in which the normal load is ramped up during scratching) were made using a commercial nanoindenter with a scratch attachment. For fracture toughness, the indentation
Figure 3.4: Wear of substrate materials vs. sliding distance for nano-scratched two-module transverse-slotted heads run at 1.5 m/s tape speed and 2.2 N tension (using MP tape A)

The technique was used. For the thin-films, a commercial nanoindenter with a cube corner indenter was used. For the substrate materials, a commercial microindenter with a Vickers indenter was used. To obtain the damage index data, the wear damage caused by a sapphire ball-on-flat test for the various materials was characterized; zero indicates low wear and five indicates heavy wear. Optical micrographs of the wear tracks for the various materials, following ball-on-flat tests, are shown in Figure 3.6. This data is used for model creation and simulations in section 3.6.

For the wear test reported in Figure 3.4, the change in the scratch depth found over the first 5 km was ignored and is not included in the plot because some of the debris created during the scratch was still present and affected the data during the period 0 to 5 km of sliding distance. All of this debris seems to have been cleared away after this first 5 km. For Al₂O₃-TiC, a wear rate is difficult to discern in Figure 3.4. In sliding with MP tape, Al₂O₃-TiC should not wear very much since the only material available at the
Figure 3.5: Summary of hardness, elastic modulus, fracture toughness, scratch resistance, and wear damage data for 5 µm thick Al₂O₃ and CZT thin films, and bulk Al₂O₃-TiC and Ni-Zn ferrite (taken from Li and Bhushan, 2001)
interface that can wear it to any significant extent is the Al$_2$O$_3$ that constitutes the tape HCAs. Everything else that is present is softer than Al$_2$O$_3$-TiC and would be more likely to be worn than to cause wear of the opposing surface. Even Al$_2$O$_3$ is not harder than Al$_2$O$_3$-TiC; it is, obviously, equal in hardness to the Al$_2$O$_3$ phase and less hard than the TiC phase. The plot shown for Al$_2$O$_3$-TiC in Figure 3.4 goes slightly negative. This may be due to the presence of thin stains near the thin-film; stains of this magnitude have been reported previously (Scott and Bhushan, 1999).

A wear rate can be estimated from the Ni-Zn ferrite data. This wear must be caused primarily by the tape’s HCAs. These are the only materials at the interface that are harder than Ni-Zn ferrite. Fitting a linear regression line to the approximately linear portion of the plot for Ni-Zn ferrite, which includes all but the first data point, gives a wear rate of 0.013 nm/km. This is in fair agreement with data found by Lakshmikumaran et al. (2000) for a similar Ni-Zn ferrite head with a different MP tape, and under different drive and environmental conditions. In that study wear rate was measured using wear-sensitive resistive elements (Dee et al., 1994).

### 3.2.2 Effects of Substrate and Thin-film Materials on PTR

Before moving into comparisons of materials, some general points must be made. Figure 3.7 shows 3-dimensional scans across the thin film region of two-module blind-slotted Al$_2$O$_3$-TiC heads run against MP tape for 5 km and 500 km. Significant PTR growth can be seen over the first 500 km. As will be shown later, the most significant growth is seen near the start of the test. PTR levels off with increasing sliding distance.

As stated earlier, the reported recession, for a given condition and sliding distance, is the
Figure 3.6: Optical images of wear tracks for the various materials following ball-on-flat tests (taken from Li and Bhushan, 2001)
average over the four imaged sites. Table 3.1 shows the PTR for each pole for the test run with a two-module blind-slotted Al₂O₃-TiC head run at 1.5 m/s tape speed and 2.2 N tension. No great variation can be seen among the poles.

<table>
<thead>
<tr>
<th>Sliding distance (km)</th>
<th>PTR (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pole 3</td>
</tr>
<tr>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>29</td>
</tr>
<tr>
<td>20</td>
<td>32</td>
</tr>
<tr>
<td>100</td>
<td>35</td>
</tr>
<tr>
<td>500</td>
<td>38</td>
</tr>
</tbody>
</table>

Table 3.1: PTR of four imaged poles for test with two-module blind-slotted Al₂O₃-TiC head with CZT poles run at 1.5 m/s and 2.2 N (using MP tape A)

PTR results obtained for different materials are now discussed. Figures 3.8 shows PTR vs. sliding distance and 2-dimensional scans (averaged over the length of a pole tip) of heads run over different distances. It shows the difference in PTR between two-module blind-slotted heads with an Al₂O₃-TiC substrate and a Ni-Zn ferrite substrate. Both heads have Ni-Fe poles. Although the profiles look much different, the PTR of the two heads is similar; the recession for the Ni-Zn ferrite head is a bit higher. Similar results are shown in Figure 3.9. Figure 3.9(a) shows data for two-module transverse-slotted heads and (b) shows data for three-module transverse-slotted heads. The trends shown in the plots of Figures 3.8 and 3.9 are typical; recession generally increases (when it does increase) at a relatively high rate near the beginning and then at a lower rate at an advanced stage. In some tests recession appears to reach a steady-state value. In both cases shown in Figure 3.9 the head with the Ni-Zn ferrite substrate shows higher
Figure 3.7: 3-dimensional SAAFM scans across the thin film region of two-module blind-slotted Al$_2$O$_3$-TiC head with CZT poles run at 1.5 m/s tape speed and 2.2 N tension (using MP tape A)
Figure 3.8: PTR vs. sliding distance as a function of substrate material for two-module blind-slotted heads run at 1.5 m/s tape speed and 2.2 N tension (using MP tape A)
differential wear. In fact, in Figure 3.9(b), the initial recession for the Ni-Zn ferrite head starts at zero, lower than the Al₂O₃-TiC head, and overtakes it relatively quickly. These results are unexpected since Ni-Zn ferrite has a hardness much closer to Ni-Fe, CZT and Al₂O₃ than Al₂O₃-TiC has (as shown in Figure 3.5). This would presumably lead to less differential wear for Ni-Zn ferrite. However, the fact that Ni-Zn ferrite is less wear resistant than Al₂O₃-TiC, as shown in Figure 3.4, should lead to the existence of more Ni-Zn ferrite wear particles at the interface, which would in turn act as additional third bodies in the three body abrasive wear mode and cause additional wear of the poles. This makes the point that material hardness matching, i.e. choosing the substrate and thin-film materials such that their hardness values are close to equal, will not reduce differential wear if a substrate is chosen that is less hard than the tape’s HCAs, because of the additional loose abrasive head particles sliding through the interface. This data also gives some indirect support to the notion that three-body particles are important in PTR. Figure 3.10 shows that little difference exists between the wear of CZT and Ni-Fe poles. Patton and Bhushan (1996) have seen this before. The result is not unexpected since the hardness values of the two films are similar. Patton and Bhushan (1996) reported a hardness (these were measured with a nanoindenter) of 8.5 GPa for a sputtered CZT and 9.0 GPa for a sputtered Ni-Fe in their study. Note that mechanical property values can vary from one deposition run to another; they depend on deposition parameters and conditions. The effect of thin-film material is also shown in Figure 3.11. In Figure 3.11(a) CZT and FeAlN pole materials deposited on single-module heads are compared, while in (b) CZT and Al₂O₃ thin films deposited on three-module transverse-slotted heads are compared. For Figure 3.11(b), results from two Al₂O₃ tests are shown because a film
Figure 3.9: (a) PTR vs. sliding distance as a function of substrate material for nano-scratched two-module transverse-slotted heads run at 1.5 m/s tape speed and 2.2 N tension (using MP tape A) and (b) recession vs. sliding distance as a function of substrate material for three-module transverse-slotted heads run at 1.5 m/s tape speed and 2.2 N tension (using MP tape A)
Figure 3.10: PTR vs. sliding distance as a function of pole material for two-module blind-slotted Al$_2$O$_3$-TiC heads run at 1.5 m/s tape speed and 2.2 N tension (using MP tape A)
thickness equal to the CZT film thickness was not available. So data shown for Al₂O₃ has a head with a film thickness a bit higher and a head with a film thickness a bit lower than the head with CZT. For all Figure 3.11 data, recession is much higher for the softer CZT thin films. This was also found in a previous study by Patton and Bhushan (1996). The hardness of FeAlN is not reported in Figure 3.5; Patton and Bhushan measured a hardness (with a nanoindenter) of 18.0 GPa. The differences in recession, it seems, can simply be explained by the differences in hardness between the materials. Relationships between wear and hardness are well established in tribology; lower hardness of a worn surface leads to higher wear. Choosing a thin-film material as close as possible in hardness to the substrate material, assuming that the head material is harder than the tape’s HCAs, should lead to minimum differential wear.

3.2.3 Effect of Thin-film Thickness on PTR

The effect of thin-film thickness is shown in Figure 3.12. Figure 3.12(a) compares two single-module heads with everything in common but their overcoat thickness. Figure 3.12(b) compares three transverse-slotted three-module heads with everything in common but their thin-film thickness. Although the trends are not as prominent as those seen with changes in material, differences are found. In Figure 3.12(a), the head with the thicker overcoat clearly shows higher recession after starting at about the same value. In Figure 3.12(b), the 40 µm thin film shows a higher recession than the 9 µm and 3 µm thin films. The initial recession for the 40 µm thin film was lower than for the other two and still grew to a higher value. No real difference is seen between 9 µm and 3 µm. The recession for both of these remained essentially unchanged for the test. In keeping with
Figure 3.11: (a) PTR vs. sliding distance as a function of pole material for single-module heads run at 4.0 m/s tape speed and 1.0 N tension (using MP tape B) and (b) recession vs. sliding distance as a function of thin-film material for three-module transverse-slotted heads run at 1.5 m/s tape speed and 2.2 N tension (using MP tape A)
Figure 3.12: (a) PTR vs. sliding distance as a function of overcoat thickness for single-module heads run at 4.0 m/s tape speed and 1.0 N tension (using MP tape B) and (b) recession vs. sliding distance as a function of thin-film thickness for three-module transverse-slotted heads run at 1.5 m/s tape speed and 2.2 N tension (using MP tape A)
the three-body abrasion theory of wear, this data suggests that abrasive particles of a size larger than the thickness of the thin film, are less able to reach the recessed thin film because they are physically prevented from doing so, i.e. at some size the thin-film thickness is low enough to prevent a significant number of the particles from entering the recess, thus mitigating wear.

3.2.4 Effects of Tape Speed, Tape Tension, Interface Contamination, and Tape Burnishing on PTR

Figure 3.13(a) shows the influence of tape speed on PTR for two-module blind-slotted Al₂O₃-TiC heads. From the plot of PTR vs. sliding distance, it seems that higher tape speed may lead to slightly lower PTR over short distances. This may occur because the air-film between the head and tape increases with an increase in tape speed; this is known as the air-bearing effect, an issue that will be addressed in section 3.3. Figure 3.13(b) shows the influence of tape tension for two-module blind-slotted Al₂O₃-TiC heads. Clearly, higher tape tension leads to higher PTR over the short term. This should come as little surprise since, in general, abrasive wear is proportional to normal force; normal force is proportional to tape tension. This dependence on normal force should prevail whether the wear occurs by way of a two-body mode, where hard particles that remain attached to the tape wear the head materials, or whether the wear occurs by way of a three-body mode.

As stated in Chapter 2, one of the drive tests was conducted in the Bell & Howell VR-3700B tape drive shown in Figure 2.1(b). This drive has been observed to be worse in particle generation than the Honeywell 96 (the drive that was used for most of the
Figure 3.13: PTR vs. sliding distance as a function of (a) tape speed (at 2.2 N tension), (b) tape tension (at 1.5 m/s tape speed), and (c) interface contamination (at 3.0 m/s tape speed and 2.2 N tension) (“Less Contamination” test was performed on Honeywell 96 and “More Contamination” test was performed on Bell & Howell VR-3700B) for two-module blind-slotted Al₂O₃-TiC heads with CZT poles using MP tape A
tests). The tape in this drive encounters more flanges and rollers in its path, which may account for the difference in loose particle generation. The influence of this additional contamination for two-module blind-slotted Al₂O₃-TiC heads is shown in Figure 3.13(c). It shows that higher contamination leads to higher PTR. This is additional evidence for three-body abrasion.

Figure 3.14 shows the effect of changing to a new tape length in the midst of a wear test after an apparent steady-state value has been reached. This test was made with a three-module transverse-slotted Al₂O₃-TiC head that has a 40 µm Al₂O₃ thin film. The issue being investigated here is whether the head has apparently reached its steady state recession because the recession has reached a level that makes it difficult for particles to reach the recessed material, or because the interface has been deprived of loose particles for some time because the tape has been burnished and new particles are not generated at a high rate. The data indicates that the recession has reached a level that makes it difficult for particles to reach, because changing tape does not have a major effect. If the absence of particles had been the dominant reason, a large increase would have been seen in recession after the tape was changed; something like the increase caused by the first tape length would have been observed.

Shown in Figure 3.15 are PTR and overcoat recession data for two-module blind-slotted Al₂O₃-TiC and Ni-Zn ferrite heads with Ni-Fe poles. The recession of the overcoat is measured at the position immediately next to the right pole, as shown in Figure 1.1. Notice that the pole material wears at a higher rate than the overcoat material in both cases even though the pole material is farther away from the air bearing surface and, presumably, encounters fewer third body particles than the overcoat material. This
happens because the pole material is softer and less wear resistant. At some point in the head’s history, PTR should become so advanced, causing the pole to encounter few wear particles, that the pole and overcoat materials would wear at the same rate. That point has not been reached for either of the heads in Figure 3.15.

3.2.5 Effect of Stain on PTR Measurement / Masking of PTR

Figure 3.16 compares the recessions in three-module transverse-slotted Al₂O₃-TiC heads caused by the two tapes, A and B. As shown in Figure 3.16(a), the recessions are quite similar. It is noteworthy however that tape B does have a tendency to stain the head in the thin-film region at times; this tendency is not seen with tape A. The reason for this difference is not known. This staining has an effect on recession measurements; recession growth plus stain growth is actually being measured at these points. Two representative AFM maps taken after 100 km are shown in Figure 3.16(b). At this point
Figure 3.15: PTR and overcoat recession for two-module blind-slotted $\text{Al}_2\text{O}_3$-TiC and Ni-Zn ferrite heads with Ni-Fe poles.
Figure 3.16: (a) Recession vs. sliding distance for two different MP tapes (A and B) for three-module transverse-slotted heads run at 1.5 m/s tape speed and 2.2 N tension (2 Al$_2$O$_3$-TiC with 40 µm Al$_2$O$_3$), and (b) three-dimensional AFM maps of head surfaces after sliding for 100 km for the two different tapes
staining was most apparent for the head run against tape B. This staining leads to an apparent decrease in recession in the period from 20 to 100 km for this head. The stain becomes less noticeable as seen with the AFM at 500 km and the increase in recession in the period from 100 km to 500 km is readily seen.

Stains of greater thickness than that seen in Figure 3.16 can appear near heads’ read-write gap for linear and rotary drives (Scott and Bhushan, 2000). This phenomenon causes significant masking of PTR in these heads. The “false” recession measured for a functioning thin-film tape head as a function of sliding distance is shown in Figure 3.17 (Kattner and Bhushan, 2001). The up and down behavior seen in this curve is not typical for tape heads that experience PTR, as shown previously. The magnitudes of change seen in “recession” shown here are in good agreement with the magnitudes of stain thickness measured by Kattner and Bhushan (2001). This is a good indication that true PTR is not being measured here. This staining has also been observed in functional rotary drives tests (Luk and Bhushan, 2001).

The PTR data shown previously was taken for dummy (non-functioning) heads. These dummy heads do not show a tendency to attract the magnitude of stains seen in Figure 3.17. A possible reason for the difference seen with heads that stain near the read-write gap and those that do not, may be the existence or absence of heat from the read-write elements. Evidence for this proposition does exist; Kattner and Bhushan (2001) have shown that stain thickness near the read element (which is known to get quite hot) is much greater than in other parts of the thin-film region.

Since the stain thickness is on the same order as PTR in some of these functioning heads, stain is a significant problem, not only because of the spacing loss that it creates,
but also because it (doubtlessly) affects PTR. This is not studied here (since only dummy heads have been used), but one suspects that it probably reduces PTR. It probably acts as a sort of coating that protects the head as it is worn and replenished as sliding proceeds.

3.3 Experimental Results for Changes in Head Slot Orientation

3.3.1 Effects on PTR

PTR for two-module heads with the two slot orientations (blind and transverse) is shown in Figure 3.18. As stated earlier, the value indicated by each graph symbol in the Figure 3.18 plots is an average of four measurements. The error bars in the plots indicate the highest and lowest PTR values of the four measurements taken for each point. Two tests were conducted for transverse-slotted heads at the same conditions to give a measure of reproducibility. As shown in Figure 3.18, the two tests yielded quite similar results. The relatively high PTR values for blind-slotted heads reported here in Figure
Figure 3.18: PTR vs. sliding distance as a function of slot orientation for two-module blind-slotted and transverse-slotted Al₂O₃-TiC heads run at 1.5 m/s tape speed and 2.2 N tension (using MP tape A)
3.18 (high relative to transverse-slotted heads) are consistent with those found in the data shown earlier. It is clear from Figure 3.18 that PTR is much lower in the case of the transverse-slotted heads. This is in spite of the fact that the same materials are used in both head types and that the thin-film geometries are approximately equivalent for the two head types. It will be shown later that head-tape spacing (thickness of the air film) for the two types is also similar.

### 3.3.2 Effects on Particle Contamination

Three types of debris were found. These include: loose particles consisting of magnetic-particle-rich and polymer-rich types, and stain (Scott and Bhushan, 1999). The head locations where the various debris types are found are shown in Figure 3.19. Magnetic-particle-rich particles are characterized by their opacity while the polymer-rich particles are characterized by their translucent appearance. These two types are loose and easily removed. Stain, by contrast, is characterized by its inability to be removed easily with a solvent. It may only be removed using vigorous mechanical action. Sample micrographs of all debris types on both heads are shown in Figure 3.20. Figures 3.19 and 3.20 show head locations ‘A’ through ‘F’. These locations are referenced in the discussion that follows.

For blind-slotted heads, magnetic-particle-rich particles are found on the regions of the head just outside the tape width. ‘A’ shows particles on the surface just outside the edge bleed slots while ‘B’ shows particles in an edge bleed slot. Most of these particles are probably generated at the locations at which they are found. It is likely that parts of the magnetic layer are worn off the tape surface by the action of the tape sliding against
Figure 3.19: Types of debris found on two-module blind-slotted and transverse-slotted heads using MP tape A; locations A to F are referenced in Figure 3.20
Figure 3.20: Debris found on surface of two-module blind-slotted (locations A to D in Figure 3.19) and transverse-slotted (locations E to F in Figure 3.19) heads using MP tape A.
the corners of the edge bleed slots. The polymer-rich particles are found at the leading
and trailing edges of tape contact with the head. Location ‘C’ shows examples of these
particles between outer bleed slots. These are likely generated at or near the thin-film
region, where the head-tape contact is closest. They are then expelled from the contact
patch by the motion of the tape. Stain may cause the most serious spacing problems
since it gathers near the pole tips. However, the thickness of the stain generated in tests
with dummy heads and MP tape A (the tape used for the results reported in this section)
is estimated to be only a few nanometers (Scott and Bhushan, 1999). A sample
micrograph of stain is shown in Figure 3.20 and was taken at the location indicated as ‘D’
in Figure 3.19. This debris has approximately the same appearance near each pole tip.
Since this type adheres to the head surface so strongly, the tape cannot swipe it out of the
contact area. Its appearance at the area of the head near the pole tips indicates that the
head-tape contact is closest at these locations. This type appears as a brown
discoloration, with no clear-cut edges. It has only been removed with diamond lapping
tape.

For transverse-slotted heads, loose particles are found almost exclusively inside
the transverse slots. A micrograph of these particles was taken at location ‘E’. The
action of the tape sliding against the slot edges causes particles to be collected. These
particles are generated there or at another location across the head surface (or at some
other point in the tape drive), to collect in the slots. As in the case of blind-slotted heads,
stain is shown to collect near the thin-film region of the transverse-slotted head. A
sample micrograph of this type is shown in Figure 3.20 and was taken at the location
indicated as 'F' in Figure 3.19. As was the case for the blind-slotted head, this stain is brown in color, has no clear-cut boundaries, and is not removed with anything short of diamond tape lapping.

Figure 3.21 shows debris maps that were generated for the magnetic-particle-rich particles (which accounts for approximately 2/3 of the loose debris found on the blind-slotted head surface) found on the blind-slotted head surface and for all loose particles found on the transverse-slotted head surface. (Note that the debris map shown for the blind-slotted head was not generated using the data for the test conducted for this study, but is taken from a previous study (Scott and Bhushan, 1999) that used a tension of 1.7 N rather than 2.2 N. All other conditions were the same as those used in this study.) The graphs show the amounts of particles covering the head in the regions along and across the heads. The data shown is for one half of a module. Most of the particles for the blind-slotted head are found in the edge blind slots. The remainder is found near them. It can also be seen (looking across the head in the tape direction) that the center region of the head collects more of this particle type than any other region. This is somewhat unexpected since the closest contact occurs at the thin-film region, away from the center. For the transverse-slotted head, all particles are found in the slots. The edges of the slots seem to clean debris from the tape, which are then trapped in the slot cavity. Particles are found in greater quantities as one moves outward toward the head region that contacts the tape edge. This is likely a consequence of the inward tape curvature resulting from the application of tape tension and the mechanical composite nature of magnetic tape. The tape makes closer, and perhaps more irregular, contact with the head at the edges than in the interior. This results in increased wear.
Figure 3.21: Magnetic-particle-rich particle distribution along and across two-module blind-slotted heads and loose particle distribution along and across two-module transverse-slotted heads in contact with MP tape A over a 100 km sliding distance (note the difference in scale between the two plots)
Table 3.2 shows differences in particle generation, in terms of area of a tape head covered by particles, and coefficient of friction, between two-module blind- and transverse-slotted heads. These tests were carried out on the Honeywell 96 drive; the coefficient of friction measurement and calculation for this drive is detailed in Appendix A. (For the blind-slotted case, the totals for magnetic-particle-rich and polymer-rich particle types were added together and listed as ‘loose particles’ in Table 3.2). The quantity of loose debris found on the transverse-slotted head surface is approximately four times greater than that found on the blind-slotted head.

The amount of stain found on the blind-slotted head is greater, while the coefficient of friction is higher for the transverse-slotted head. As shown in the micrographs of Figure 3.20, stain collects more uniformly along the head length for the transverse-slotted head, as compared to the blind-slotted head. This seems to be a result of the more uniform contact along the head width. Blind-slotted heads have intermittent bleed slots along their width. This leads to lower head-tape spacing in some regions of the thin-film (regions in line with two bleed slots) than in other regions (those regions not situated between two bleed slots or, stated differently, the regions in line with the lands); this will be shown later. Figure 3.22 shows, schematically, the locations of the regions in line with bleed slots and the regions in line with lands. In the tests conducted here, this non-uniformity in contact along the width leads to the existence of intermittent stain fields which are individually larger than those found for the same thin-film area of transverse-slotted heads. The higher coefficient of friction for the transverse-slotted head seems also to be a result of this difference in contact uniformity.
<table>
<thead>
<tr>
<th>Slot Orientation</th>
<th>Area covered&lt;sup&gt;*&lt;/sup&gt; Loose Particles (mm&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Area covered&lt;sup&gt;*&lt;/sup&gt; Stain (mm&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Coefficient of Friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blind</td>
<td>0.53</td>
<td>1.4</td>
<td>0.09</td>
</tr>
<tr>
<td>Transverse</td>
<td>1.95</td>
<td>1.0</td>
<td>0.14</td>
</tr>
</tbody>
</table>

<sup>*</sup>The total area available for debris coverage is ~78 mm<sup>2</sup>

Table 3.2: Debris quantities and coefficient of friction for two-module blind- and transverse-slotted heads in contact with MP tape A over a 100 km sliding distance

![Diagram](image)

Figure 3.22: Locations of regions in line with slots and regions in line with lands in two-module blind-slotted heads
3.3.3 Effects on Head-Tape Spacing

Head-tape spacing is plotted for the two head orientations (using MP tape A), as a function of tape tension and speed, in Figure 3.23. The plotted points are an average of the data collected for the forward and reverse directions of the tape cycler. In cylindrical heads, such as this one, head-tape contact is established at high tension and low speed while large head-tape spacing occurs at low tension and high speed (a phenomenon commonly referred to as “tape flying” as noted earlier) (Bhushan, 1996; Chan et al., 1995). For the blind-slotted head the spacing was found for two regions: (1) the region in line with bleed slots, where the magnetic poles are placed, and (2) the region in line with the lands, where no writing takes place. The area in line with the slots clearly exhibits lower spacing. This spacing is only a weak function of tension and speed.

Though tape flying in the regions in line with the lands is undesirable in general, close spacing is only required in the pole regions (in line with bleed slots). In the transverse-slotted head, a measurement was taken in only one location corresponding to the pole location of a working head, since the spacing is uniform across the head (direction perpendicular to the direction of tape motion). The contour performance, as shown in Figure 3.23, of the blind-slotted head (in line with slots) is almost identical to that of the transverse-slotted head.

Figure 3.24 shows the head-tape spacing maps generated during the spacing measurement. The drive conditions used to generate these were 1.5 m/s tape speed and 1.9 N tape tension. These conditions are nearly equal to those used in the wear tests. Relative uniformity in spacing can be seen in the blind-slotted, in line with the slots, and
in the transverse-slotted heads. The middle image in Figure 3.24 shows the area at the interface of the slot and land. The higher spacing in line with the lands is evident.

For conditions of 1.9 N tension and 1.5 m/s speed, the spacing for both heads is approximately equal, about 40 nm. Since contact pressure is inversely proportional to head-tape spacing, contact pressure should also be approximately equal for the two heads. These results indicate that neither head-tape spacing nor contact pressure can be used to explain differences in wear seen in the two head types.

3.3.4 Relationship Between PTR and Particle Contamination

The edges of transverse slots act as cleaners and result in a large collection of loose particles in the slots. It is proposed that the presence of these slots results in the absence of many of the loose particles that would otherwise have been present at the interface. Head-tape spacing, thin-film geometry, and the head materials used, are similar for the two head types. Therefore, these do not explain any differences in behavior between the head types.

PTR is lower for transverse-slotted heads. Since all other factors are similar for the two heads, the availability of loose particles at the interface, particles that could be used as the third body in the three-body wear mode that is believed to cause PTR, seems to be the important factor to explain the difference. This explanation is illustrated in Figure 3.25.
Figure 3.23: Influence of tape tension and speed on head-tape spacing of two-module blind- and transverse-slotted heads run against MP tape A
Figure 3.24: Grayscale maps showing head-tape spacing at 1.5 m/s tape speed and 1.9 N tension for blind- and transverse-slotted heads run against MP tape A (tape direction is forward)
Figure 3.25: The cleaning action of transverse slots is illustrated; fewer particles are transmitted to the thin-film region, which leads to lower PTR.

Figure 3.26: Number of airborne particles vs. time for a drive test (using MP tape A) with a period of no head-tape contact followed by a period of head-tape contact, and finally followed by a period of no head-tape contact; these particles are collected with a laser particle counter.
3.4 Experimental Results for Particle Extraction (Laser Particle Counter and Optical Microscopy)

Figure 3.26 shows the number of airborne particles per cubic centimeter that are collected by the laser particle counter over time. Data was taken for a period before head-tape contact (but with the drive running), followed by an hour-long period of head-tape contact, and followed lastly by a period of no head-tape contact. Great variability was found over time and no measurable difference was seen between the periods of no head-tape contact and the period of head-tape contact. Since the airborne particles generated during wear cannot be separated from the background, the numbers that were found, in the range of approximately 6 – 28 particles / cc, can only be taken as an upper bound on the actual number that were generated. The reason for the apparent periodicity seen in Figure 3.26 is unknown.

Table 3.3 shows data acquired from the image analysis of the optical micrographs of particles that were solvent-extracted from the head specimens. The extraction test micrographs provide individual particle information (size, type, etc.) that could not be provided by the image analysis of the particles on the head surface that was discussed earlier. The lengths of the particles shown in Table 3.3 are the lengths of the major axes of the ellipses fitted to the particles in the image analysis software.

SEM micrographs of typical solvent-extracted particles found after a drive test and after an environmental exposure test with Ni-Zn ferrite are shown in Figure 3.27. (The backgrounds in these micrographs are the collection filters.) It is clear from the data in Table 3.3 that almost all of the particles extracted after the drive tests are below 100 µm in length and that the range 10 – 20 µm has a larger number of particles than any
other range. Table 3.3 also shows that a substantial majority of the solvent-extracted particles are generated in the head-tape contact. Only about ten percent as many particles are extracted after an exposure to the drive environment. After cleaning, only a negligible number of particles are found. EDX was used to characterize the particles. Representative EDX spectra are shown in Appendix C. Most of the particles found on the filters following the drive tests are tape particles; the elements Fe, Al, Cl, F, Si, C, and O were found. Other particles, originating from the environment, consisted of Ca, F, C, and O. In the handful of EDX spectra that were acquired, head particles were not detected. This suggests, not surprisingly, that most wear particles originate from the tape. It also suggests that particles that originate from the head (these particles must certainly be generated in the Ni-Zn ferrite head since we can measure a wear rate; see section 3.2.1) perhaps do not stick to the interface as well as tape particles (tape particles may be

<table>
<thead>
<tr>
<th>Test</th>
<th>Percentage of particles in different length ranges (%)</th>
<th>Number of particles / 100 mm² of filter</th>
<th>Percentage of filter area covered (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive test with Al₂O₃-TiC</td>
<td>22 between 4.09 - 10 µm, 34 between 10 - 20 µm, 13 between 20 - 30 µm, 14 between 30 - 50 µm, 12 between 50 - 100 µm, 6 above 100 µm</td>
<td>385</td>
<td>0.215</td>
</tr>
<tr>
<td>Drive test with Ni-Zn ferrite</td>
<td>18 between 4.09 - 10 µm, 37 between 10 - 20 µm, 18 between 20 - 30 µm, 16 between 30 - 50 µm, 10 between 50 - 100 µm, 2 above 100 µm</td>
<td>568</td>
<td>0.238</td>
</tr>
<tr>
<td>Hour-long exposure to environment with Ni-Zn ferrite</td>
<td>14 between 4.09 - 10 µm, 21 between 10 - 20 µm, 10 between 20 - 30 µm, 23 between 30 - 50 µm, 22 between 50 - 100 µm, 10 above 100 µm</td>
<td>44</td>
<td>0.040</td>
</tr>
<tr>
<td>&quot;Clean&quot; Ni-Zn ferrite</td>
<td>0 between 4.09 - 10 µm, 67 between 10 - 20 µm, 11 between 20 - 30 µm, 11 between 30 - 50 µm, 0 between 50 - 100 µm, 11 above 100 µm</td>
<td>5</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Table 3.3: Number and size data taken from image analysis of optical micrographs of particles extracted from three-module transverse-slotted heads after 5.5 km sliding tests with MP tape A
Figure 3.27: SEM micrographs of particles extracted from a two-module transverse-slotted Ni-Zn ferrite head (a) after a 5.5 km (one-hour) wear test with MP tape A and (b) after an hour-long exposure to the drive environment.
statically charged and also tend to be stickier than head particles) and may simply be swept out of the interface by the motion of the tape or fall out when the head is removed from the drive following a test.

3.5 Experimental Results Showing the Use of Ultrathin DLC Coatings in the Mitigation of PTR

Because PTR results from the differential wear of the heads’ phases and is a consequence of the differing material and wear properties of these phases, the deposition of a hard coating on the surface reduces PTR. It gives ultimate mechanical property matching; all phases have the same surface material properties. Before moving on to the drive-level data, data from nanoindentation and ball-on-flat tribometer experiments on ultra-thin DLC is reviewed. Mechanical property data, critical load data, and damage indices are shown in Figure 3.28 (Li and Bhushan, 1999a, 1999b; Bhushan, 1999a; Sundararajan and Bhushan, 1999). The measurements and tests used to obtain this data were reviewed in section 3.2.1. In the case of these ultra-thin coatings, the critical load often signals the cracking or delamination of the coating. DLC coatings deposited by the following techniques were tested: filtered cathodic arc (FCA), ion beam (IB), RF-biased electron cyclotron resonance plasma chemical vapor deposition (ECR-CVD), and RF-sputtered (SP). Data for silicon (Si) and Al₂O₃-TiC are also shown for comparison. FCA coatings exhibit the highest hardness, elastic modulus, and fracture toughness, followed by the ECR-CVD, IB, and SP coatings. The SP coatings show poor scratch and wear resistance. FCA and ECR-CVD coatings are quite good in these respects, while IB
coatings have intermediate properties. All of the coatings, except SP, may be sufficient to protect magnetic recording heads based on this data (Li and Bhushan, 1999b).

Figure 3.29 shows plots of PTR and overcoat recession versus sliding distance and two-dimensional scans of two-module blind-slotted heads run over different sliding distances, as shown in previous figures. The benefit of the DLC coating is clear from the PTR plot. For the uncoated head, PTR reaches almost 60 nm, after starting from about 15 nm, in just 600 km of sliding. The 10 nm thick coated head, whose PTR starts at about 40 nm, does not reach a PTR as high as 55 nm until 4200 km of sliding. The difference between the uncoated and coated heads is even clearer in the overcoat recession plot. While the overcoat recession of the uncoated head reaches 25 nm in 600 km, that of the coated head has reached only a few nanometers when the test was terminated at 4200 km. Note that overcoat recession is negative for much of the test. This means that the overcoat is higher than the substrate. To some extent this is an artifact of the head shape and the measurement. The head has a finite radius and the point at which overcoat recession is measured is at the top of the radius in the 2-D images. If the profile were perfectly circular, meaning that no recession of any kind could be seen, the measured overcoat recession would be negative because of the head curvature. Only a first-order Planefit (discussed in section 2.1.3.2) was used to post-process the data shown here.

Figure 3.30 shows differences among uncoated, 5, 10, and 20 nm thick coated transverse-slotted heads. The PTR of the uncoated head starts at 11 nm and reaches a value of over 30 nm after 750 km of sliding. Its overcoat recession starts at about 5 nm and reaches a value of over 25 nm over that distance. The PTR of the 5 and 20 nm thick
Figure 3.28: (a) Mechanical property data, obtained using a nanoindenter, (b) critical load data, obtained using a nanoindenter scratch test, and (c) damage index ratings, obtained using a ball-on-flat test for various ultrathin DLC coatings (taken from Bhushan, 1999a)
Figure 3.29: PTR and overcoat recession of two-module blind-slotted uncoated and 10 nm thick DLC coated (deposited by ion beam) heads run at 1.5 m/s tape speed and 2.2 N tension (using MP tape A)
coated heads are still below 30 nm out to sliding distances of 3600 km and 4150 km, respectively. The 10 nm thick coated head has a PTR that is a little higher, but it stays relatively steady over the course of the test. As in the case of the blind-slotted heads, the overcoat recessions of the coated heads are much lower than the recession of the uncoated head. Differences are seen between the coated heads also. The overcoat recession of the 5 nm thick coated head rises to almost 15 nm by the end of the test, while that of the 10 nm thick coated head rises to over 20 nm. Overcoat recession of the 20 nm thick coated head is much lower, only about 6 nm.

PTR and overcoat recession for the uncoated heads increase monotonically with sliding as shown in previously in this chapter. The plots of PTR and overcoat recession for the coated heads have a different shape. For the coated heads, PTR and overcoat recession initially decrease with sliding, up to approximately 500 to 1000 km. In this regime it appears that the DLC fully covers both the substrate and the thin-film. The difference in wear rates between the substrate and thin-film, which leads to decreasing PTR, is likely due to differences in contact pressure over the head width. The substrate should encounter higher contact pressure than the thin-film since the thin-film is recessed from the air bearing surface. Since the surface material properties of the substrate and thin-film are the same (since both are fully covered by DLC), the substrate must wear at a higher rate. The difference in wear rate may also be due in part to differences in adhesion strength. Al₂O₃-TiC is known to have difficulty in adhesion. At a sliding distance of approximately 500 to 1000 km, PTR and overcoat recession begin to increase. At this point it appears that the DLC must have been significantly worn off of the substrate. Figure 3.31 depicts an Auger electron spectrum obtained from the substrate of the head.
Figure 3.30: PTR and overcoat recession of two-module transverse-slotted uncoated, 5 nm, 10 nm, and 20 nm thick DLC coated (deposited by ion beam) heads run at 1.5 m/s tape speed and 2.2 N tension (using MP tape A)
that initially had a 20 nm DLC coating, after 1000 km of sliding. AlO\textsubscript{x}, SiO\textsubscript{x}, and Ti, which clearly come from the substrate, are found, while carbon is not. Since the DLC has been worn off of the substrate, the tape slides against the substrate itself (which wears more slowly) and the DLC coated thin-film. Differences in material and wear properties rather than differences in contact pressure dominate differential wear in this regime. The approximate hardness and elastic modulus values for bulk Al\textsubscript{2}O\textsubscript{3}-TiC, as measured by nanoindentation and shown in Figure 3.5, are 30 GPa and 450 GPa, respectively. The approximate values for ion beam DLC, as measured by nanoindentation and shown in Figure 3.28, are 19 GPa and 150 GPa, respectively.

Figure 3.31: AES spectrum of the substrate of the 20 nm thick coated two-module transverse-slotted head showing loss of DLC coating (surface was sputter etched for 30 seconds to remove about 2 nm of surface contamination; primary beam energy = 1.5 keV)
Figure 3.32: AFM surface height plots of representative pole tip regions of 10 nm thick and 20 nm thick coated two-module transverse-slotted heads
Figure 3.32 shows AFM surface height plots of the thin-film regions of 10 nm thick and 20 nm thick coated transverse-slotted heads. Large darkly shaded segments, corresponding to low surface height, are seen in the thin-film region for the 10 nm thick coated head. Fewer of these are seen for the 20 nm thick coated head. This piecewise removal of material suggests delamination as the ultimate cause of coating failure. Similar plots of uncoated heads show no such piecewise removal.

The deposition of DLC itself is found to produce an unintended effect. Initial PTR (PTR before the wear test) was found to be higher after deposition than before it. This may be seen for the head profiles shown in Figure 3.33. For the 5 nm, 10 nm, and 20 nm thick coated two-module transverse-slotted heads, PTR increases from 12 nm, 9 nm, and 12 nm, before deposition, to 24 nm, 26 nm, and 23 nm, after deposition, respectively. This increase was found to be due, in large part, to the precleaning etching done just prior to deposition of DLC. The precleaning etch time for these three heads was two seconds. For the 10 nm coated two-module blind-slotted head, the precleaning etch time was fifteen seconds. Its PTR was found to increase from 12 nm, before deposition, to 38 nm, after it.

One objective of this DLC study is to make a judgment about the feasibility of using 20 nm thick coatings in real drives. Assuming a head lifetime of five years, a 50 % duty cycle, and a tape speed of 2 m/s, the lifetime of a head in terms of tape length is about 150,000 km. In this study, coatings of thinner than 20 nm were used to accelerate wear tests. It was believed that the wear might be steady and that the wear life of the coatings would be in proportion to the coating thickness. This was found to be false. Both a 5 nm and a 10 nm thick coating fail after 4000 km at a tension of 2.2 N, as judged
from overcoat recession data. Since a 1.1 N tension is commonly used in real drives, the real life of these coatings is probably closer to 8000 km, as wear rate is approximately proportional to normal load (Bhushan, 1999b). Judging again from overcoat recession data, the 20 nm thick coating has not failed. A 20 nm thick coating should have a wear life longer than 8000 km in a real drive. As stated earlier, these coatings appear to fail by delamination, rather than by a steady wear process. Scratch tests, results of which were reported in Figure 3.28, were performed on these coatings (deposited on silicon). These tests showed that the critical load (the load associated with coating delamination) is similar for the 5 nm, 10 nm, and 20 nm coatings. This suggests that a 150 000 km sliding distance life for a 20 nm coating is out of reach. However as tape tensions are reduced, which is required for thinner media, and as media is made less abrasive, DLC may become a viable solution.
3.6 Analytical Model of Micro/Nanoscale Differential Wear in Tape Heads

3.6.1 Model

An analytical model for micro/nanoscale differential wear is now presented. The objective is to derive a model that explains and predicts the wear history of a material based on its material and wear properties. In developing this model for differential wear, the wear mode for the head thin-film material is assumed to be three-body abrasive wear, for reasons given in previous sections. The wear mode for the head substrate material is assumed to be a combination of adhesive and two- and three-body abrasive wear. Bhushan (1996) found that this is true for heads sliding against MP tape. Wear is also assumed to occur by plastic deformation. Plastic wear, whether adhesive or abrasive, is governed by the empirical relation shown previously in Eq. (1.2).

\[
V = \frac{kWL}{H}
\]

where \( V \) is the wear volume, \( k \) is the dimensionless wear coefficient, \( W \) is the normal force, \( L \) is the sliding distance, and \( H \) is the hardness of the worn surface. Bhushan and Lowry (1995) have shown that \( V \propto W \), \( V \propto L \), and \( V \propto 1/H \) for various head materials sliding against CrO\(_2\) and other particulate tapes. These relationships are shown in Figure 3.34. The recession data given in this paper also demonstrates that wear occurs by primarily plastic deformation. Thin-film Al\(_2\)O\(_3\) wears at a higher rate than Ni-Zn ferrite (resulting in recession), in spite of the fact that Ni-Zn ferrite has a much lower fracture toughness, as previously shown in Figure 3.5. Lower fracture toughness should lead to a higher wear rate for Ni-Zn ferrite if the wear is primarily caused by brittle fracture. These results suggest that wear is primarily governed by the difference in hardness.
Figure 3.34: Plots of head (a) wear rate for a Mn-Zn ferrite head slid against CrO\(_2\) tape as a function of tension (normal load or contact pressure), (b) wear depth for a Mn-Zn ferrite head slid against various tapes as a function of sliding distance, and (c) wear rate for various head materials slid against CrO\(_2\) tape as a function of head material hardness (taken from Bhushan and Lowry, 1995)
between thin-film $\text{Al}_2\text{O}_3$ and Ni-Zn ferrite, i.e. thin-film $\text{Al}_2\text{O}_3$ wears at a higher rate primarily because it is softer, indicating plastic wear. The wear tracks found by Li and Bhushan (2001) in their ball-on-flat tests and shown in Figure 3.6, using the materials used for heads in this study, indicate that wear is primarily plastic, even for the brittle Ni-Zn ferrite. The low loads used in these tests and in tape heads in service, probably accounts for the plastic-dominated wear. Evans and Marshall (1981) indicate that wear of brittle materials (ceramics) at low loads (below the threshold loads needed to cause propagation of lateral cracks as discussed in Chapter 1) involves plastic cutting. Hsu and Shen (1996) have found that, in some ceramics, low loads result in wear by microabrasion rather than by brittle fracture. The existence of a transition between low-load plastically-dominated and high-load brittle fracture-dominated wear is also discussed by Hutchings (1992). As was noted in Chapter 1, other workers have used Eq. (1.2) for ceramics at low loads (Andersen et al., 1997; Rutherford and Hutchings, 1997).

Assuming that wear occurs uniformly over the substrate, an expression for wear depth for the substrate material may be derived using Eq. (1.2),

$$d_{\text{sub}} = \frac{k_{\text{sub}}p_{\text{sub}}L}{H_{\text{sub}}} \quad (3.1)$$

where $d_{\text{sub}}$ is the wear depth for the substrate, $p_{\text{sub}}$ is the nominal contact pressure on the substrate, and $k_{\text{sub}}$ and $H_{\text{sub}}$ are the dimensionless wear coefficient and the hardness of the substrate, respectively. The nominal contact pressure experienced by the head depends on the tape tension, the head radius, the tape width, and the portion of the load supported by the hydrodynamic air film between the head and tape. This air film thickness is
typically 40 nm for most of the heads used in this study (as discussed in section 3.3.3). If the air film is ignored, the nominal contact pressure on the substrate may be calculated as

\[ p_{\text{sub}} = \frac{T}{R_{\text{head}} w_{\text{tape}}} \quad (3.2) \]

where \( T \) is tape tension, \( R_{\text{head}} \) is the head contour radius, and \( w_{\text{tape}} \) is the tape width.

A wear depth expression similar to Eq. (3.1) may be written for the thin-film material,

\[ d_f = \frac{k_f p_f L}{H_f} \quad (3.3) \]

where the subscript ‘\( f \)’ denotes the parameters for the thin-film material that were described previously for the substrate material. The change in recession depth with sliding distance is just the difference between the wear rates of the thin-film material and the substrate material,

\[ \frac{dr}{dL} = \frac{k_f p_f}{H_f} - \frac{k_{\text{sub}} p_{\text{sub}}}{H_{\text{sub}}} \quad (3.4) \]

where \( r \) is recession depth. While the other parameters in Eq. (3.4) are approximately constant for given materials and interface properties, \( p_f \) changes over time. Pressure \( p_f \) is reduced as the recession depth \( r \) becomes larger. Three-body abrasive particles have more difficulty reaching the thin-film as it becomes more recessed, giving a reduced contact pressure in the thin-film region. As demonstrated in section 3.1, tape cannot bend into a recess to a significant extent. Therefore, the portion of the load carried by the thin-film material decreases as the recession increases. This portion of the load that is no longer supported by contact with the thin-film region may be supported by additional air-film pressure and/or contact with the substrate material. Because the thin-film regions
are so narrow, the apparent area of contact between the tape and substrate is approximately 100 to 2000 times larger than that between the tape and thin film. This means that the portion of the total load applied by the tape that is supported by the thin-film region is quite low, even for zero recession (assuming the same nominal contact pressure for the substrate and thin-film at zero recession). So even large changes in contact pressure in the thin-film region lead to insignificant changes in the contact pressure on the substrate and in the head-tape spacing. Therefore, contact pressure on the substrate and head-tape spacing will be taken as constants with changes in recession depth for all analysis that follows. An analysis showing the way in which $p_f$ changes with recession depth $r$ follows.

Figure 3.35 is a schematic that shows an interaction between a loose abrasive particle, the tape surface, and the recessed thin-film surface, during which the thin-film material is worn. Most of the loose abrasive particles will originate from the tape, as shown in section 3.4. Some will originate from the head. Assuming that the contacts between the particle and tape surface and the particle and thin-film surface are plastic, that the contacting asperities are spherical, and that tape bending caused by the particle interaction is negligible, the tape and thin-film surfaces deform according to Eqs. (3.5) and (3.6).

\[
W_{pi} = A_{ni}H_i = pd_{ni}(2R_{ni} - d_n)H_i \tag{3.5}
\]

\[
W_{pi} = A_{ti}H_t = pd_{ti}(2R_{ti} - d_t)H_t \tag{3.6}
\]

where $W_{pi}$ is the force that a particle exerts on the thin-film surface, and $A_{ni}$ and $A_{ti}$ are the projected areas between the particle and thin-film surface and between the particle
Figure 3.35: Schematic showing the interaction between loose abrasive particle, tape surface, and recessed thin-film surface
and tape surface for an individual particle, respectively. \( H_f \) and \( H_t \) are the hardness values for the thin-film and tape surfaces, respectively. \( \delta_f \) and \( \delta_t \) are the deformations of the thin-film and tape surfaces caused by the contact with a particle, respectively. \( R_{fi} \) and \( R_{ti} \) are the spherical asperity contact radii of a particle in contact with the thin-film and tape, respectively. As shown in Figure 3.35, the geometric relationship among the dimensions is described by Eq. (3.7).

\[
d_{fi} + d_{ti} + h + r = t_i
\]  

(3.7)

where \( h \) is the thickness of the air film between the two surfaces and \( t_i \) is the thickness of the particle. It is also assumed that the thickness of the air film, \( h \), does not change because of the particle interaction. Combining Eqs. (3.5), (3.6), and (3.7) to eliminate the deformation variables yields Eq. (3.8).

\[
R_{fi} - \left( \frac{p^2 R_{fi}^2 H_f^2 - pH_f W_{pi}}{pH_f} \right)^{1/2} + R_{ti} - \left( \frac{p^2 R_{ti}^2 H_t^2 - pH_t W_{pi}}{pH_t} \right)^{1/2} = t_i - h - r
\]

(3.8)

Solving Eq. (3.8) for \( W_{pi} \) gives an expression that describes the relationship between \( W_{pi} \) and \( r \); we get

\[
W_{pi}(r) = A \left\{ B + Cr + \left[ D + Er + Fr^2 \right]^{1/2} \right\} \left\{ G + Cr + \left[ D + Er + Fr^2 \right]^{1/2} \right\}
\]

(3.9a)

where

\[
A = \frac{-pH_f}{(H_f - H_t)^2}
\]

\[
B = (t_i - h)H_f - R_{fi} H_f - R_{ti} H_t
\]
\[ C = -H_t \]  

\[ D = R_{fi} H_t^2 + (t_i^2 + h^2)H_t H_i - 2(R_{fi} + R_{ti})t_i H_t H_i + 2(R_{fi} + R_{ti})h H_t H_i + 2R_{fi} R_{ti} H_t H_i - 2t_i h H_t H_i + R_{ti}^2 H_i^2 \]

\[ E = 2(R_{fi} + R_{ti} + h - t_i)H_t H_i \]

\[ F = H_t H_i \]

\[ G = (t_i - h - 2R_{fi})H_t + R_{ti} H_t - R_{ti} H_i \]

As will be shown shortly, \( W_{pi} \), calculated using Eq. (3.9), decreases with an increase in recession depth \( r \) or a decrease in particle thickness \( t_i \). Load \( W_{pi} \) also decreases with a decrease in either \( R_{fi} \) or \( R_{ti} \), or with an increase in air film thickness \( h \). Load \( W_{pi} \) remains virtually unchanged with changes in either thin film hardness \( H_f \) or tape hardness \( H_t \).

Before the load \( W_{pi} \) can be predicted using Eq. (3.9), an estimate of particle thickness must be made. Patton and Bhushan (1997), using MP tape in a commercial rotary drive, have measured the magnitude of short duration losses in read-head signal (signal dropouts), many of which are believed to be caused by particles sliding through the interface (thus causing a local separation between the head and tape for as long as the particle remains in the read gap). Typical signal loss magnitudes ranged from 4 – 12 dB, with more of them near the 4 dB end, for a written signal wavelength of 0.6 \( \mu \)m. Using
the Wallace equation (1951), which relates signal loss to physical separation (among other things), the particle sizes that would cause dropouts of these magnitudes would range from approximately 40 to 130 nm in thickness, with more near the 40 nm end. So in generating plots of $W_{pi}$ vs. recession three particle thickness values are used: 50, 75, and 100 nm. Plots for these three particle thickness values are shown in Figure 3.36. The other parameters in Eq. (3.9) used to create these plots are shown in Table 3.4. The assumed thin-film material is $\text{Al}_2\text{O}_3$. The contact radii $R_{fi}$ and $R_{ti}$ are difficult to determine; we assume contact radii to be equal to the radius of MP tape HCAs (~100 nm), which are believed to be the primary abrasives.

Assuming that the nominal contact pressure between the tape and substrate surface is equal to the nominal contact pressure between the tape and thin-film surface when the recession is zero, i.e. $p_{\text{sub}} = p_{f}(r=0)$, the number of contacts capable of being supported by the thin-film surface may be found as

$$n_{\text{max}} = \frac{p_{\text{sub}} \cdot W_{\text{tape}} \cdot W_{f}}{W_{ip}(r = 0)}$$

(3.10)

where $n_{\text{max}}$ is the maximum number of contacts (or particles) capable of being supported and $W_{f}$ is the width of the thin-film region. The actual number of particles may be less than this number $n_{\text{max}}$, but that would only change the value of $n$; it would have no effect on the problem analysis. The small extra load that would not be supported by the thin-film region would simply be supported by additional air-film pressure and/or contact with the substrate material with negligible effects on $p_{\text{sub}}$ and head-tape spacing $h$, as explained earlier. It is assumed here that the number of particles present will be exactly equal to the number $n_{\text{max}}$. 

111
\[
p_f(r) = \frac{n_{\text{max}} W_{\text{ip}}(r)}{w_{\text{tape}} w_f}
\]  

(3.11)

It is further assumed that the number of particles \( n_{\text{max}} \) will remain constant over the course of a wear test. This assumption has some support from Scott and Bhushan (1999) and Hunter and Bhushan (2001). They found that the rate of debris generation is approximately constant over time. Of course this assumption is not quite true. When the recession is low, significant direct thin-film surface-tape contact occurs; this contact does not occur at high recession. This effect is not taken into account here. This leads to an underestimate of the magnitude of the slope of the \( p_f \) vs. \( r \) curve, especially at low recession depths.

All assumptions and simplifications used in the model are summarized here: (1) head wear occurs by primarily two-body and three-body abrasive and adhesive (for substrate), and three-body abrasive (for thin film) modes and wear occurs by plastic deformation, (2) wear for the individual head materials is uniform, (3) air-film pressure is disregarded in the calculation of nominal contact pressure, (4) particle deformation is disregarded, (5) air-film thickness is independent of wear particle thickness and recession depth, (6) for a wear event, the contact between the particle and tape, and between the particle and the head’s thin-film material is plastic, (7) the contact pressure on the substrate is equal to that on the thin film when the recession depth is zero, (8) the number of particles in contact with the thin film does not change over sliding distance and is equal to the maximum number required to support the contact pressure at a recession depth of zero, and (9) direct contact between the tape and thin film is disregarded. The required inputs for the model are \( H_{\text{sub}}, H_f, H_t, R_{\text{ft}}, R_{\text{tt}}, h, T, k_{\text{sub}}, w_{\text{tape}}, R_{\text{head}}, w_f, \) and \( t_i \).
Figure 3.36: Modeled variation of load on a single particle vs. recession depth for various particle thickness values using nominal values for the rest of the parameters (these are listed in Table 3.4)

<table>
<thead>
<tr>
<th>H&lt;br&gt;&lt;sub&gt;of Al₂O₃ (GPa)&lt;sup&gt;a&lt;/sup&gt;&lt;/br&gt;</th>
<th>H&lt;sub&gt;b&lt;/sub&gt; (GPa)&lt;sup&gt;b&lt;/sup&gt;</th>
<th>R&lt;sub&gt;a&lt;/sub&gt; (nm)&lt;sup&gt;c&lt;/sup&gt;</th>
<th>R&lt;sub&gt;ti&lt;/sub&gt; (nm)&lt;sup&gt;c&lt;/sup&gt;</th>
<th>h (nm)&lt;sup&gt;d&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.4</td>
<td>0.3</td>
<td>100</td>
<td>100</td>
<td>40</td>
</tr>
</tbody>
</table>

<sup>a</sup>Fig. 3.5; <sup>b</sup>Li and Bhushan (1997); <sup>c</sup>approx. rad. of HCA, Chapter 1; <sup>d</sup>Chapter 3

Table 3.4: Nominal values used for calculation of W<br><sub>pπ</sub> in Figure 3.36
Expanding on the discussion of Eq. (3.4), recession may be calculated using the following differential equation,

\[
\frac{dr}{dL} = \frac{k_I \rho_f (r)}{H_f} - \frac{k_{sub} \rho_{sub}}{H_{sub}} \quad r \leq (\text{largest } t_i) - h
\]  

(3.12a)

\[
\frac{dr}{dL} = 0 \quad r > (\text{largest } t_i) - h
\]  

(3.12b)

with initial condition \( r(L=0) = r_o \), where \( r_o \) is the initial recession. The analytical solution of Eq. (3.12a) requires the solution of the following integral,

\[
\int \frac{1}{W_{qp}(r)} dr
\]  

(3.13)

This integral is difficult to solve analytically, so Eq. (3.12) was solved numerically. A recursive formula may now be derived to simulate wear,

\[
\Delta r_j = \left[ \frac{k_I}{H_f} \rho_f (r_{j-1}) - \frac{k_{sub}}{H_{sub}} \rho_{sub} \right] \Delta L
\]  

(3.14a)

\[
r_j = r_{j-1} + \Delta r_j
\]  

(3.14b)

where \( j = 1 \) to number of iteration steps. For Eq. (3.14a), \( \rho_f (r_{j-1}) \) is calculated using Eqs. (3.2), (3.9), (3.10), and (3.11). For each simulation reported in the next section, a single particle size is used. All simulations reported in the next section use a step size, \( \Delta L \), of 1 km. No appreciable difference is seen in the resulting curves for a step size of 1 km and step sizes smaller than 1 km. The program for this algorithm was written for MATLAB. The program code is given in Appendix D.
3.6.2 Model Results and Comparison with Experiment

Figure 3.37 shows a comparison between experimental results shown earlier and model results for a uniform particle thickness of 75 nm (the intermediate size used in Figure 3.36). The wear coefficients used in the model for the substrates Al$_2$O$_3$-TiC and Ni-Zn ferrite, $k_{\text{sub}}$, are near zero and $1.7 \times 10^{-8}$, respectively; these were derived using Eq. (3.1) and data in Figures 3.4 and 3.5. These and the other parameters used in the model to obtain the curves shown in Figure 3.37 are listed in Table 3.5. To obtain these Figure 3.37 model curves, the thin-film wear coefficients $k_f$ are chosen such that the model recessions at 500 km match the experimentally obtained recessions at 500 km as closely as possible. These values of $k_f$, which are really the output from the model, are also shown in Table 3.5. Similarities and differences may be seen between the experimental and model curves. The rate of increase in recession decreases over sliding distance for both the experimental and model curves. The rate of increase in the early period, from about 0 to 20 km, is clearly lower for the model curves. This difference is most likely due to the simplicity of the assumed particle size distribution (all particles were taken to be the same size) and the failure to account for the significant contact between the tape and thin-film material at low recession depth (a point alluded to in the last section). As will be shown later, changing the particle size in the model may lead to much different results. For Figure 3.37(a) and (b), the slope of the experimental and model curves near 500 km match each other fairly well. This is not the case for the curves shown in Figure 3.37(c), where the recession is fairly low overall and the influence of the aforementioned size distribution issue is more evident.
Figure 3.37: Comparison between experimental data and model results for a uniform particle thickness, \( t_i = 75 \) nm, where the thin-film wear coefficients \( k_f \) are chosen such that the model recessions at 500 km match the experimentally obtained recessions at 500 km as closely as possible; recession vs. sliding distance for 1.5 m/s tape speed and 2.2 N tension with MP tape A using three-module transverse-slotted (a) Ni-Zn ferrite head with 10\( \mu \)m \( \text{Al}_2\text{O}_3 \) thin film, data from Fig. 3.9(b) (model uses \( k_f = 4 \times 10^{-8} \)), (b) \( \text{Al}_2\text{O}_3\)-TiC head with 5\( \mu \)m CZT thin film, data from Fig. 3.11(b) (model uses \( k_f = 3.5 \times 10^{-8} \)), and (c) \( \text{Al}_2\text{O}_3\)-TiC head with 40\( \mu \)m \( \text{Al}_2\text{O}_3 \) thin film, data from Fig. 3.12(b) (model uses \( k_f = 1 \times 10^{-8} \)). The number of particles at all times is assumed to be \( n_{\text{max}} \).
Table 3.5: Model parameters and resulting $k_f$ value used for creation of curves in Figure 3.37

<table>
<thead>
<tr>
<th>Head</th>
<th>$H_{sub}$ (GPa)$^a$</th>
<th>$H_i$ (GPa)$^a$</th>
<th>$H_f$ (GPa)$^b$</th>
<th>$R_i$ (nm)$^c$</th>
<th>$R_f$ (nm)$^c$</th>
<th>$h$ (nm)$^d$</th>
<th>$T$ (N)</th>
<th>$k_{sub}$ $^e$</th>
<th>$k_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni-Zn ferrite / 10 µm Al$_2$O$_3$</td>
<td>11.3</td>
<td>10.4</td>
<td>0.3</td>
<td>100</td>
<td>100</td>
<td>40</td>
<td>2.2</td>
<td>1.7 x 10$^8$</td>
<td>4 x 10$^8$</td>
</tr>
<tr>
<td>Al$_2$O$_3$-TiC / 5 µm CZT</td>
<td>30.2</td>
<td>8</td>
<td>0.3</td>
<td>100</td>
<td>100</td>
<td>40</td>
<td>2.2</td>
<td>0</td>
<td>3.5 x 10$^8$</td>
</tr>
<tr>
<td>Al$_2$O$_3$-TiC / 40 µm Al$_2$O$_3$</td>
<td>30.2</td>
<td>10.4</td>
<td>0.3</td>
<td>100</td>
<td>100</td>
<td>40</td>
<td>2.2</td>
<td>0</td>
<td>1 x 10$^8$</td>
</tr>
</tbody>
</table>

$^a$Fig. 3.5; $^b$Li and Bhushan (1997); $^c$approx. rad. of HCA, Chapter 1; $^d$Chapter 3; $^e$derived using Eq. (3.2) and Figs. 3.4 & 3.5

The differences in the values of $k_f$ derived from the model (shown in Table 3.5) make sense in terms of the number of particles available for wear of the various films. The Ni-Zn ferrite head with the Al$_2$O$_3$ thin film has a $k_f$ that is four times larger than that for the Al$_2$O$_3$-TiC head with the same thin-film material. While both Al$_2$O$_3$ thin films wear during contact with Al$_2$O$_3$ HCAs from the tape, the Ni-Zn ferrite head also wears (unlike the Al$_2$O$_3$-TiC head, for which no measurable wear could be detected), feeding additional abrasive particles into the interface, which leads to additional wear of the Al$_2$O$_3$ thin film in the Ni-Zn ferrite head; this probably accounts for this difference in $k_f$.

This demonstrates that attempting to match the hardness values of the head substrate and thin-film materials does not generally lead to less differential wear if, in lowering the hardness of the substrate, it was made less hard than the tape’s HCAs. Since the Al$_2$O$_3$-TiC heads with the 3 and 9 µm thick Al$_2$O$_3$ thin films showed essentially no recession growth over their test duration, $k_f$ for these two films must be taken as zero, while $k_f$ for
the 40 µm film has a non-zero value. Differences in the ease with which particles are able to enter the thin-film region account for this disparity in $k_f$. As shown in Table 3.3, most of the optically detected loose particles fall into ranges above 10 µm in length. Particles in those ranges cannot fit into the 3 and 9 µm thin-film regions. These explanations for differences in $k_f$ are illustrated in Figure 3.38. The Al$_2$O$_3$-TiC head with the CZT thin film shows a substantially higher $k_f$ than the Al$_2$O$_3$-TiC head with the Al$_2$O$_3$ thin film. The reason for this is not evident, but it is consistent with the ball-on-flat test data shown in Figures 3.5 and 3.6. Thin-film CZT showed more damage than the thin-film Al$_2$O$_3$ despite the fact that the difference in their hardness values is not very great.

Figure 3.39 shows model results of the influences of particle thickness, tape tension, thin-film hardness, and thin-film wear coefficient on recession. For these comparisons, the Ni-Zn ferrite head with a 10 µm Al$_2$O$_3$ thin film with the parameter values shown in the first row of Table 3.5 is used as the standard. For each comparison, only the parameter being studied is varied. An increase in particle thickness leads to an increase in recession. This influence becomes less great as the particle becomes larger. A larger tape tension leads to a higher recession; this was shown experimentally in section 3.2.4. The influence of tape tension is probably underestimated here since an increase in tape tension leads to an increase in particle generation (Scott and Bhushan (1999); Hunter and Bhushan (2001)), which should increase $k_f$. Increasing thin-film hardness and/or decreasing $k_f$ leads to a decrease in recession. Figure 3.40 shows different modeled wear histories for the same head (the Ni-Zn ferrite head with a 10 µm Al$_2$O$_3$ thin film with the parameter values shown in the first row of Table 3.5), with different initial recessions: 0, 15, and 30 nm. All of the curves are clearly approaching
Figure 3.38: Explanations for differences in thin-film wear coefficient $k_f$

- **High $k_f$**
  - Existence of fewer particles at the interface lead to fewer contacts, resulting in lower wear

- **Low $k_f$**
  - Thicker thin film allows a greater number of potentially abrasive particles to wear thin film
Figure 3.39: Results generated by the model showing the effects of particle thickness, tape tension, thin-film hardness, and thin film wear coefficient; the modeled standard (nominal) head used for comparison is three-module transverse-slotted Ni-Zn ferrite with 10 $\mu$m Al$_2$O$_3$ thin film, (model parameter values for this head are shown in first row of Table 3.5) run against MP tape A and assumed particle size of 75 nm. The number of particles at all times is assumed to be $n_{max}$. 
the same value, a value lower than 30 nm. Recession actually decreases for the modeled head with an initial recession of 30 nm. Recall that this behavior was seen experimentally by Tsuchiya and Bhushan (1995), as shown in Figure 3.2.

For Ni-Zn ferrite heads, whose substrates wear, all of these trends hold for both rate of recession growth and saturated recession. For Al$_2$O$_3$-TiC heads however, which experience little or no substrate wear, the model predicts that the saturated recession will be nearly or completely independent of tape tension, thin-film hardness, and thin-film wear coefficient (unless it is zero). The model predicts that their saturation points depend on the size of the thickest particles that they encounter. It also predicts that the recession saturation will be higher for Al$_2$O$_3$-TiC heads than for Ni-Zn ferrite heads (or any other heads with substrates that wear). Experimental results in this dissertation, where significant recession differences are found among Al$_2$O$_3$-TiC heads for changes in tape tension and thin-film hardness, suggest that each of these heads reach their saturation points at very different sliding distances. Experimental results also suggest that Ni-Zn ferrite heads generally reach recession saturation much more quickly than Al$_2$O$_3$-TiC heads.

3.6.3 Future Model Development

Future work could be carried out to improve the model. As stated in the previous section, an improvement in the assumed particle distribution and an accounting for changes in the direct contact between the tape and thin-film surface with changes in recession, are probably required. A numerical contact mechanics model that uses actual surface profiler data of the two surfaces may be used to accomplish this improvement.
Figure 3.40: Results generated by the model showing the effect of initial recession depth; the modeled standard (nominal) head used for comparison is three-module transverse-slotted Ni-Zn ferrite with 10 µm Al₂O₃ thin film, (model parameter values for this head are shown in first row of Table 3.5) run against MP tape A and assumed particle size of 75 nm. The number of particles at all times is assumed to be n_{max}.

(Bhushan, 1998). Determination of the thin-film wear coefficients is another difficulty in using this model as a predictive tool. These coefficients would primarily have to be derived by experiment, although some relationships may be used. As stated earlier, thin-film thickness, wear of the substrate material (which influences the number of available three-body particles) and tape tension may be used to predict the thin-film wear coefficient.

3.7 Summary

Ample evidence exists that three-body abrasion is the cause of thin-film wear, and therefore PTR, in tape heads. Real area of contact measurements show that contact
between a tape and a recessed region (on the same order as a typical PTR) is quite low, implying that three-body abrasion must be the cause of PTR. Tests indicate that the third bodies are primarily tape particles.

At long sliding distances, PTR approaches a steady-state value that depends on the sliding materials, their topography, the head-tape spacing, the head geometry, and the abrasive particles that are present, and not on initial PTR. Heads with thin-film materials that have a hardness approaching that of the substrate show lower PTR than heads with softer thin-film materials. This was seen in comparisons between thin-film CZT and thin-film FeAlN, and between thin-film CZT and thin-film Al₂O₃. However, reducing the hardness of the substrate to a value closer to that of the pole does not reduce PTR. The fact that additional debris from the substrate is created, leading to the existence of more loose particles at the interface (for use as third-body abrasives), seems to offset the benefit of the material property matching. This was seen in tests run with heads using the relatively soft Ni-Zn ferrite (as compared to Al₂O₃-TiC) as a substrate material.

Lowering the thickness of the head’s thin-film region prohibits entry for many abrasive particles into the thin-film region, and thus leads to less differential wear. In the tests conducted for this dissertation, a total thin-film thickness of ~10 to 20 µm was shown to at least slightly reduce recession when compared to a thin film thickness of ~30 to 40 µm.

PTR increases with an increase in drive contamination, an increase in tape tension, or a decrease in tape speed. All of these results are consistent with a three-body abrasive wear mechanism. (Of course, some of these results, taken separately, are also consistent with other wear mechanisms.)
A number of points were made in the study of slot orientation. The edges of transverse slots act as cleaners and result in a large collection of loose particles in the slots. It is proposed that the presence of these slots results in the absence of many of the particles that would otherwise have been at the interface. Head-tape spacing, thin-film geometry, and the head materials used, are similar for the two head types. Therefore, these do not explain any differences in behavior between the head types. PTR is lower for transverse-slotted heads. Since all other factors are similar for the two heads, the availability of loose particles at the interface, particles that could be used as the third body in the three-body wear mode that is believed to cause PTR, seems to be the important factor to explain the difference.

In micro/nanomechanical experiments, ultra-thin DLC, deposited using various techniques, performed well enough for possible use on tape heads to mitigate PTR. For data processing drives requiring very thin coatings (~20 nm), the application of DLC coatings, deposited by ion-beam, to tape heads, reduces PTR over short sliding distances in drive tests. However, before long the DLC is worn off of the substrate and PTR increases. When the DLC on the thin-film fails, which occurs by local delamination, thin-film wear increases more quickly. Although these coatings would probably not last for the lifetime of a tape head now, they could be useful in the future, as tape tensions and abrasivities are reduced.

The analytically derived model of differential wear has potential as a predictive tool if the various wear coefficients are known. The analytically derived model shows that each of the following leads to higher recession: increasing the thickness of three-body particles, increasing tension, decreasing thin-film hardness, and increasing the thin-
film wear coefficient. An increase in thin-film wear coefficient can be caused by an increase in thin-film thickness or an increase in the number of particles at the interface. The model also predicts that initial recession depth will have no influence on steady-state recession depth, if all other parameters are equal.
4.1 Tape-Write Head Corrosion

Figure 4.1(a) shows a typical CZT metal pair of a clean uncoated head that was not subjected to corrosion testing. Figure 4.1(a) also shows a corresponding uncoated head after exposure to a BC II test for twenty days. An obvious dark deposit can be seen on the thin-film region, especially over the metal pairs. An SEM micrograph of a typical deposit is shown in Figure 4.1(b). The mechanism that causes this sort of product is known as uniform attack (Uhlig and Revie, 1985). As opposed to a localized type of attack, like pitting corrosion (which has been found to be particularly important in indoor corrosion (Abbott, 1990)), uniform attack results in widespread chemical change of the surface. As shown in the AES spectrum in Figure 4.2, the deposit consists of chlorine, which comes from the Cl$_2$ gas in the BC II test, and carbon. The deposit is probably composed of cobalt, and perhaps other materials in the thin-film, as well. Note that a primary beam energy of 1.0 keV is used in this analysis. A higher energy could not be used because the head is an insulator. If cobalt makes up any part of the deposit, it cannot be seen in this spectrum since its excitation energies are too high. (The large peaks for cobalt occur at over 700 eV). Similar deposits, also consisting of chlorine and
Figure 4.1: (a) CZT metal pair of an uncoated head (not exposed to corrosion testing) and an uncoated head after exposure to a BC II test for 20 days, and (b) a typical head corrosion deposit on top of a CZT metal pair.
carbon, may be seen on the coated heads after exposure to a BC II test for twenty days. Typical deposits from the 5 nm and 10 nm thick coated heads are shown in Figure 4.3. Very few such deposits are found on the 20 nm thick coated head after exposure. The size and severity of deposits on the uncoated head are beyond those seen on the coated heads. As shown in Figure 4.1(a), large deposits can be seen on the Al$_2$O$_3$ thin-film of the exposed head. These cannot be seen on the coated heads. Note the difference in size between the deposits shown on the exposed uncoated head in Figure 4.1(a) and those shown on the coated heads in Figure 4.3. The number of metal pairs (out of twenty) that showed deposits under an optical microscope, for each head, were: twenty for the uncoated head, twelve for the 5 nm thick coated head, seventeen for the 10 nm thick coated head, and two for the 20 nm thick coated head. The excellent performance of the 20 nm thick coating, even over the performance of the 5 and 10 nm thick coatings, is
Figure 4.3: Coated heads after exposure to a BC II test for 20 days

Optical micrographs of coated heads after exposure to BC II tests for 20 days

5 nm thick coated head

10 nm thick coated head

25 µm
likely a result of the completeness of the coverage of the underlying metal. The 5 and 10 nm thick coatings probably do not cover the metal as completely. Holes in the coating, leading to the underlying metal, likely serve as the initiation sites for corrosion (Sundararajan and Bhushan, 1999). An AES analysis shows that only carbon (probably from the DLC coating) exists on the surface of a metal pair, which appears clean under optical observation, of the exposed 20 nm thick coated head. It appears that no chemical changes, other than those deposits that may be viewed optically (like those seen in Figure 4.3), take place on the surface of the coated heads.

Figure 4.4 shows deposits found on the CZT sections of an uncoated head after exposure to a 60°C / 90% RH test for forty-eight days. This appears to be a case of pitting corrosion, a localized type of attack where the rate of corrosion is greater at some areas than at others (Uhlig and Revie, 1985). The AES spectrum, shown in Figure 4.5, of one deposit shows that it consists of the same materials as the metal pair. No deposits are found on any of the coated specimens, with either optical microscopy or AES, after exposure to 60°C / 90% RH tests.

4.2 Tape Corrosion

As stated in Chapter 2, tape specimens were subjected to corrosion tests in two ways: (1) outside a cartridge, as coupons, and (2) inside a cartridge. The cartridge specimens were taken from the outer-most wrap on the tape spools. Unless stated otherwise, the results in this section are reported for the coupon specimens. Figure 4.6(a) shows optical micrographs for MP tape coupons, for uncoated ME tape coupons, and for uncoated ME tape cartridge specimens before and after a twenty day BC II test. Many
Figure 4.4: Deposits found on a CZT metal pair of an uncoated head after exposure to a 60°C / 90% RH test for 48 days

Figure 4.5: AES spectrum of a deposit on an uncoated head after exposure to a 60°C / 90% RH test for 48 days (primary beam energy = 1.5 keV)
Figure 4.6: (a) Micrographs taken before and after 20 day BC II test, and (b) deposits on ME tape w/o DLC after exposure to a BC II test for 20 days
large stony deposits may be seen on the surface of the uncoated ME tape. Similar deposits are seen on all of the ME tape coupon samples, regardless of exposure time or whether the tape has a DLC coating. They are also found on all the outer-most wraps of the ME cartridge specimens, although they are less densely packed on the surface than they are on the surface of the coupon specimens. Similar deposits are not found on the surface of MP tape. SEM micrographs of these large deposits on uncoated ME tape after a twenty day BC II test are shown in Figure 4.6(b). SEM micrographs of smaller deposits (in the submicron range) on coated ME tape, after exposure to a two day BC II test, are shown in Figure 4.7. (Cracks in the DLC coating are also visible. It is unknown whether this cracking is a result of physical handling of the tape or of the corrosion test.) An AES spectrum of the large deposit shows that it consists of sulfur, carbon, and oxygen. (Figure 4.8 shows AES spectra of tapes before and after exposure).

Sulfur comes from the H$_2$S gas in the BC II test. It is usually not considered a very important pollutant in office environments, which the BC II test is meant to model. H$_2$S is used in the test primarily for its synergistic effect. It helps to bring out the effect of the more important Cl$_2$ gas (Abbott, 1987, 1990). The fact that this deposit consists of so much sulfur (relative to the amount found in other samples) and contains no chlorine, along with the fact that it has such an unusually large, stony appearance, makes it very likely that these deposits are just by-products of the test, and are not important in tape corrosion. It is not known, however, why these deposits are not attracted to MP tapes.

Figure 4.8(c) and Figure 4.8(d) also show AES spectra of coated ME tape before and after a twenty day BC II test. In the spectrum taken after the test, cobalt from the tape surface underlying the DLC can be seen, along with a trace amount of sulfur. Cobalt
Figure 4.7: Metal oxide deposits on ME tape w/ DLC after exposure to a BC II test for 2 days
cannot be seen in the spectrum taken before the test. (Since the cobalt peaks seen in Figure 4.8(d) are small, scans were repeated several times, and the result was the same each time.) This change suggests that a corrosion reaction has taken place. Pits in the DLC serve as corrosion sites. These reactions account for the products shown in Figure 4.7. An AES spectrum of one such product is shown in Figure 4.9. These products appear to be primarily oxides of cobalt. They are found on ME tape coupon specimens, regardless of exposure time. No chlorine products were found on tape specimens exposed to BC II tests. A fluorine peak is seen in the AES spectrum of the coated ME tape before exposure, as shown in Figure 4.8(c). This peak, which likely comes from the lubricant, is not seen after exposure (Figure 4.8(d)), suggesting that the lubricant has been removed.

Tape was also taken from the center of the exposed tape cartridges for analysis. No corrosion products could be found for any of the tapes taken from these locations. It seems that the physical barrier provided by the cartridge and the tape wraps provides corrosion protection. It is not clear, however, whether twenty days (the duration of these tests) is sufficient time for the pollutant gases to diffuse into the closed cartridge. So, while the exposure of coupons is more severe than a real time exposure, the exposure of cartridges may be less severe than a real time exposure.

Following the nineteen day 60°C / 90% RH tests, little change can be seen optically, as shown in Figure 4.10. However, a change in surface topography is found for uncoated ME tape with the use of AFM. Figure 4.11 shows surface topography of ME tape with and without DLC, before and after T & H tests. While no significant change is seen in the coated ME tape, the RMS roughness of uncoated ME tape changes from 4.0
Figure 4.8: AES spectra of (a) unexposed ME tape w/o DLC (primary beam energy = 3.0 keV), (b) a large deposit on ME tape w/o DLC after exposure to a BC II test for 20 days (primary beam energy = 1.0 keV), (c) unexposed ME tape w/DLC (primary beam energy = 2.0 keV), and (d) the surface of ME tape w/DLC after exposure to a BC II test for 20 days (primary beam energy = 2.0 keV)
Figure 4.9: AES spectrum of oxide deposits on ME tape w/ DLC after exposure to a BC II test for 2 days (primary beam energy = 1.5 keV)

nm to 9.2 nm. MP tape does not experience a change. AES analysis shows no chemical difference between the unexposed and exposed specimens of any tape after 60°C / 90% RH tests.

4.3 Summary

The addition of an ultra-thin DLC coating deposited by ion beam has been shown to increase the corrosion resistance of magnetic tape-write heads. The coating inhibits contact between environmental pollutants and the metal surfaces of the head, where corrosion reactions, involving the pollutant Cl₂, occur. A 20 nm thick coating protects better than a 5 or 10 nm thick coating, both of which exhibit about equal performance. The benefit of DLC coatings on ME tape, in terms of corrosion resistance, is not as substantial. Coated and uncoated ME tape coupons showed significant evidence of
Figure 4.10: Micrographs taken before and after 19 day 60°C / 90% RH test
Figure 4.11: 10 x 10 µm AFM scans of unexposed ME tape w/ DLC before and after 19 day 60°C / 90% RH test, unexposed ME tape w/o DLC before and after 19 day 60°C / 90% RH test
corrosion. Metal oxides have been found on the surface of both following Battelle Class II tests. Tape specimens taken from cartridges show less evidence of corrosion. The less aggressive tests of elevated temperature and humidity do show a benefit of DLC coatings on ME tape. A change in surface roughness of uncoated ME tape after these tests, serves as evidence of change. No such changes are seen in coated ME tapes. No significant changes are found in MP tapes as a result of any of the corrosion tests.
5.1 Micro/Nanoscale Differential Wear in Tape Heads

Experimental results support the notion that three-body abrasion of the thin-film material is the cause of differential wear (PTR) in tape heads. PTR generally increases as sliding proceeds. In general, it increases at a high rate near the beginning of sliding and increases at a lower rate as the tests go on. Choosing a substrate material that is harder than the tape’s HCAs (which are the primary abrasives) should reduce differential wear; material hardness matching will not reduce differential wear if a substrate is chosen that is less hard than the HCAs because the substrate will wear, leading to the existence of additional three-body substrate particles. Choosing a pole material that has a hardness as close as possible to the hardness of the substrate, without reducing the hardness of the substrate to a value below the hardness of the tape’s HCAs, should reduce differential wear. Lowering the thickness of the head’s thin-film region prohibits entry for many abrasive particles into the thin-film region, and thus leads to less differential wear.

No large differences are found in PTR with changes in tape speed. Any differences that are found are probably caused by changes in head-tape spacing.
associated with the speed change. Higher tape tension leads to higher PTR; this is result of the increased contact pressure. More particle contamination at the interface also leads to higher PTR.

Differences in the number of loose abrasive particles available at the interface explain why PTR is higher in the case of blind-slotted heads than it is in the case of transverse-slotted heads. The influences of contact pressure, head-tape spacing, head geometry (aside from slot orientation), and materials were ruled out because they were virtually identical for the two head types.

DLC coatings, deposited by ion beam, of 5, 10, and 20 nm thickness lessen the problem of pole tip recession seen in uncoated tape heads. The 20 nm thick coating performs best, while, the 5 and 10 nm thick coatings perform about equally well. Coatings wear off of the substrate first and then wear off of the thin-film region. While coatings initially wear by an abrasive and/or adhesive mode, failure ultimately occurs by coating delamination. Although it is difficult to estimate wear life with the use of accelerated tests, like the ones conducted in this study, it appears that ultra-thin DLC coatings may not provide protection for the lifetime of a tape head.

The analytically derived model of differential wear has potential as a predictive tool if the various wear coefficients are known. The model, which assumes plastic wear of the thin-film region by three-body abrasion and plastic wear of the head substrate material by adhesive and (two- and three-body) abrasion, finds the changes in contact pressure on the thin-film region as a function of recession depth. These changes in contact pressure are then used in a recursive formula to predict recession depth (at the next iteration). The model shows that each of the following leads to higher recession:
increasing the thickness of three-body particles, increasing tension, decreasing thin-film hardness, and increasing the thin-film wear coefficient. An increase in thin-film wear coefficient can be caused by an increase in thin-film thickness or an increase in the number of particles at the interface. The model also predicts that initial recession depth will have no influence on steady-state recession depth, if all other parameters are equal. Most of these model results are verified by the experiments carried out as part of the work for this dissertation.

Future work would probably focus on improvement of the model. An improvement in the assumed particle distribution and an accounting for changes in the direct contact between the tape and thin-film surface with changes in recession, are probably required. A numerical contact mechanics model that uses actual surface profiler data of the two surfaces may be used to accomplish this improvement. Determination of the thin-film wear coefficients is another difficulty in using this model as a predictive tool. These coefficients would primarily have to be derived by experiment, although some relationships may be used. Thin-film thickness, wear of the substrate material (which influences the number of available three-body particles) and tape tension may be used to predict the thin-film wear coefficient.

5.2 Corrosion of Tape-Write Head and Tape

Microscopy has been shown to be useful in discerning the effects of a corrosive environment on materials used in magnetic recording. Its use serves as a complement to the measurement of magnetic performance, as a function of corrosion, carried out by past researchers. The addition of an ultra-thin DLC coating deposited by ion beam has been
shown to increase the corrosion resistance of magnetic tape-write heads. The coating inhibits contact between environmental pollutants and the metal surfaces of the head, where corrosion reactions, involving the pollutant Cl₂, occur. A 20 nm thick coating protects better than a 5 or 10 nm thick coating, both of which, as in the case of coating wear, exhibit about equal performance. The benefit of DLC coatings on ME tape, in terms of corrosion resistance, is not as substantial. Coated and uncoated ME tape coupons showed significant evidence of corrosion. Metal oxides have been found on the surface of both following Battelle Class II tests. Tape specimens taken from cartridges show less evidence of corrosion. The less aggressive tests of elevated temperature and humidity do show a benefit of DLC coatings on ME tape. A change in surface roughness of uncoated ME tape after these tests, serves as evidence of change. No such changes are seen in coated ME tapes. No significant changes are found in MP tapes as a result of any of the corrosion tests.
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APPENDIX A

COEFFICIENT OF FRICTION CALCULATION

Shown in Figure A.1 is a schematic of tape wrapped over a head. For the Honeywell 96 drive, friction force is measured using a strain gage load cell. Friction force, \( F \), is the force measured with the four strain gages arranged in a full Wheatstone bridge. An excitation voltage of 5V is applied to the circuit. The output from the Wheatstone bridge circuit is amplified by a factor of 5000, using a signal-conditioning amplifier. Output is recorded on an Omega chart recorder. The load cell was calibrated using a dial force gage.

In order to estimate the wrap angle, \( \theta \), the wrap length, \( L \), is measured using a pair of vernier calipers. Then (in degrees):

\[
\theta \approx \frac{L}{2\pi R} (360)
\]

The normal force, \( N \), exerted on the head is:

\[
N \approx 2T \sin \left( \frac{\theta}{2} \right)
\]

So:

\[
\mu \approx \frac{F}{2T \sin \left( \frac{\theta}{2} \right)}
\]

where \( T \) is the tape tension
T is the tape tension

Figure A.1: Schematic showing tape wrapped over a head
SAAFM PRINCIPLES OF OPERATION


The SAAFM may be thought of as an ultra-sensitive profilometer that operates with an extremely low applied force. A piezoelectric tube scans a very sharp probe that is mounted on a cantilever over the sample surface. An interferometric detection system mounted on the end of the piezo tube senses the deflection of the cantilever as features in the sample are encountered. The control system varies the voltage applied to the piezo to keep the cantilever deflection nearly constant as the probe is scanned over the sample. The variation in voltage applied to the piezo is directly proportional to the variation in height.

Figure B.1 shows the cantilever deflection detection system. The laser diode emits light from the top, Beam 2, and bottom, Beam 1. The light emitted from the bottom of the laser is reflected off the cantilever and back into the laser. The reflective cantilever forms an external resonant cavity with the laser. The intensity of the beam emitted from the top of the laser varies according to the phase difference in the light returned from the external resonant cavity. The phase difference depends on the path
length between the cantilever and the laser diode. The light detected by the photodiode, then, provides a measure of the variation in the path length of the reflected beam, which can be caused by a cantilever deflection.

During operation the sharp probe is scanned over the surface in one direction, the fast scan direction, at a slight angle, for a specified distance. After this distance is reached the probe is moved in the opposite direction, also at a slight angle. Since the probe is scanned at a slight angle, it slowing moves in the direction opposite to the fast scan direction, across the sample. This direction is referred to as the slow scan direction. The image is captured when the probe has been scanned over the sample to the specified distance in the slow scan direction.

The operation of the SAAFM is quite similar to the operation of other AFMs. One significant difference is in the placement of the piezo material. In most AFMs, the sample to be scanned is placed on the piezo material whereas the SAAFM has the piezo material attached to the interferometric detection system. Since the sample does not sit on top of the piezo material in the SAAFM, the SAAFM can simply be placed on top of any sample, regardless of the size.
Figure B.1: Cantilever deflection detection system for SAAFM (taken from Anon., 1991)
APPENDIX C

SAMPLE EDX SPECTRA OF LOOSE PARTICLES

As stated in Chapters 2 and 3, EDX was used to chemically analyze the loose particles that were extracted from the head. Two chemically distinct particle types were found: tape and environmental dust. For tape particles, the elements Fe, Al, Cl, F, Si, C, and O were detected. For the particles originating from the environment, the elements Ca, F, C, and O were detected. A representative spectrum of each type is shown in Figures C.1 and C.2. Au and Pd peaks also show up in the spectra. These derive from the gold-palladium coating that was deposited to improve sample conduction; the particles were situated on insulating plastic filters.
Figure C.1: SEM micrograph showing the location of EDX analysis and the EDX spectrum for a tape particle
Figure C.2: SEM micrograph showing the location of EDX analysis and the EDX spectrum for a particle originating from the environment
APPENDIX D

COMPUTER PROGRAM FOR PREDICTION OF RECESSION DEPTH

The program used to predict recession depth or PTR was written for MATLAB. The program is called ‘PTR.m’. The listing is given on the following two pages. It uses the recursive formula Eq. (3.12) from Chapter 3. As recession changes, the contact pressure in the thin-film region changes. Modeling this requires the recursive algorithm used here. The theory and assumptions can be found in Chapter 3 and in comment lines throughout the program. As defined in Chapter 3, the program requires the following inputs: the initial recession, $H_{sub}$, $H_f$, $H_t$, $R_{fi}$, $R_{it}$, $h$, $T$, $k_{sub}$, $w_{tape}$, $R_{head}$, $w_f$, $\Delta L$, and $t_i$. The program also requires a value for $k_f$. For some of the model curves shown in Chapter 3, $k_f$ values were chosen (by trial and error) such that the model recessions at 500 km matched the experimentally obtained recessions at 500 km as closely as possible. In this sense, the values of $k_f$ are really the output from the model for these cases. For other model data generated and shown in Chapter 3, a value of $k_f$ was assumed and some of the other parameters ($t_i$, $T$, and $H_f$) were varied to study their influences.

Figure C.1 shows typical data generated using a plotting algorithm available in MATLAB.
clear

r(1) = 0;               % initial recession (nm)
Hf = 10.4E+9;     % thin-film hardness (Pa)
Ht = 0.3E+9;       % tape hardness (Pa)
Hsub = 11.3E+9; % head substrate hardness (Pa)
ti = 75E-9;           % particle thickness (m)
h = 40E-9;           % head-tape spacing (m)
Rfi = 100E-9;      % radius of particle contact with thin film (m)
Rti = 100E-9;      % radius of particle contact with tape (m)
kf = 4E-8;           % wear coefficient for thin film, dimensionless
ksub = 1.7E-8;    % wear coefficient for substrate, dimensionless
T = 2.2;               % tape tension (N)
Rhead = 0.01;     % head contour radius (m)
wtepe = 0.0127;   % tape width (m)
wf = 10E-6;        % nominal contact width between tape and thin film (m)
dL = 1000;         % increments of sliding distance used for recursive solution (m)

k = 500000/dL; % number of iterations needed for calculation to 500 km

x = linspace(0,500,k+1);  % sliding distance vector, 0 to 500 km

Psub = T/(Rhead*wtepe); % nominal contact pressure on substrate

% Wip is the load on an individual particle. The equation for Wip that follows assumes
% that the contacts between the particle and thin film and the particle and tape are
% plastic, and that the thin film and tape deform to accommodate a particle that slides
% through the interface. Particle deformation, tape bending and changes in head-tape
% spacing that might be caused by the sliding particle are not considered.

% The following equations for A, B, C, D, E, F, and G are intermediate calculations.

A = -pi*Hf/(Hf-Ht)^2;

B = (ti-h)*Ht - Rfi*Hf - Rti*Ht;

C = -Ht;

D = Rfi^2*Ht^2 + (ti^2+h^2)*Ht^2 + 2*(Rfi*Rti)*ti*Hf*Ht + 2*(Rfi+Rti)*h*Hf*Ht ... + 2*Rfi*Rti*Hf*Ht + Rti^2*Ht^2;
\[ E = 2(R_{fi} + R_{ti} + h - ti) \cdot H_f \cdot H_t; \]
\[ F = H_f \cdot H_t; \]
\[ G = (ti - h - 2R_{fi}) \cdot H_t + R_{fi} \cdot H_f - R_{ti} \cdot H_t; \]
\[ \text{Wipzero} = A \cdot (B + D^{1/2}) \cdot (G + D^{1/2}); \quad \% \text{Wip at a recession of zero} \]
\[ n = P_{sub} \cdot \text{wtape} \cdot \text{wf} / \text{Wipzero}; \quad \% \text{n is the number of particles estimated to be in the thin-film region. The nominal contact pressure on the thin-film region is assumed to be equal to that on the substrate at a recession of zero. The number of particles that account for this known nominal pressure, for the given calculated Wpi (at zero recession) for the individual particles, is calculated here. This number is used in subsequent calculations of the nominal pressure on the thin film as it changes over time (as the recession increases).} \]

\[
\text{for } j = 2:k+1 \]
\[
\text{Wip} = A \cdot (B + C \cdot (r(j-1) \cdot 1E-9) + (D + E \cdot (r(j-1) \cdot 1E-9) + F \cdot (r(j-1) \cdot 1E-9)^2)^{1/2}) \cdot (G + C \cdot (r(j-1) \cdot 1E-9) + (D + E \cdot (r(j-1) \cdot 1E-9) + F \cdot (r(j-1) \cdot 1E-9)^2)^{1/2});
\]

\[ \text{if } \text{Wip} < 0; \quad \% \text{physically Wip cannot be negative, but the expression above yields a negative number if the recession is greater than the saturation point} \]
\[ \text{Wip} = 0; \quad \%
\]
\[ \text{else} \]
\[
\text{Wip} = A \cdot (B + C \cdot (r(j-1) \cdot 1E-9) + (D + E \cdot (r(j-1) \cdot 1E-9) + F \cdot (r(j-1) \cdot 1E-9)^2)^{1/2}) \cdot (G + C \cdot (r(j-1) \cdot 1E-9) + (D + E \cdot (r(j-1) \cdot 1E-9) + F \cdot (r(j-1) \cdot 1E-9)^2)^{1/2});
\]
\[ \text{end} \]
\[ \% \text{This is the new Wip for the new recession at the jth iteration} \]
\[ \text{Pf}(j-1) = (n \cdot \text{Wip}) / (\text{wtape} \cdot \text{wf}); \]
\[ \% \text{Pf}(j-1) \text{ is the nominal pressure on the thin-film region for the new recession at the jth iteration} \]
\[ \text{dr} = ((k_f \cdot \text{Pf}(j-1) / H_f) - (k_{sub} \cdot P_{sub} / H_{sub})) \cdot dL \cdot 1E+9; \]
\[ \% \text{dr is the additional recession calculated for the jth iteration} \]
\[ \text{r}(j) = \text{r}(j-1) + \text{dr}; \]
\[ \% \text{r}(j) \text{ is the new recession after the jth iteration} \]
\[ \text{end} \]
% print data;
  x = x';
  r = r';
  [x r]

% plotting algorithm

plot(x, r, 'r.')
axis([0,500,0,35])
title('Recession vs. sliding distance')
xlabel('sliding distance, km')
ylabel('recession, nm')
Figure D.1: Typical data plot from ‘PTR.m’ program; the parameters used to create this plot are those shown in the program listing.
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