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The Remanent State of Recorded Tapes

Abstract: Measurements are reported on the in-plane and the perpendicular components of the remanence a tape acquires on passing through the steady field of a recording head. The tape coatings were oriented and unoriented particles of γ-Fe_2O_3, oriented CrO_2 and unoriented Co-substituted γ-Fe_2O_3. The two writing heads used had $10 \mu m$- and $2.25 \mu m$-gaps, respectively. In each case the in-plane magnetization increases at first with increasing writing current, and eventually reaches a peak that is less than the maximum in-plane remanence produced on the same sample by an electromagnet. For higher values of writing current, in-plane magnetization in the tape actually decreases. The perpendicular remanence is not large enough to explain the difference between the in-plane remanence acquired from the head and the remanence acquired in a magnet.

The perpendicular component of the field from the writing head is shown to have two adverse effects on the remanence of the tape. First, it produces a perpendicular magnetization that ranges from 2 percent to 15 percent of the in-plane component. Second, it causes a reduction in the in-plane component to occur near the surface of the tape closest to the writing head. The reduction can be as large as 15 percent of the maximum in-plane remanence and will obviously have an adverse effect on recording performance, particularly at high densities.

Introduction

The separation between a recorded tape and the reading head results in a signal loss which increases rapidly with distance. It is important to be able to determine the separation accurately, as a first step toward reducing it. Interferometric methods are currently in vogue [1], but these suffer from the need for either a transparent head or a transparent tape.

Using a plated disk, Wallace [2] in 1951 obtained experimentally, and attempted to justify theoretically, a loss of signal which depended exponentially on separation. This relationship has been used to determine the flying height by measurement of signal output as a function of wavelength and determination of values of read-head gap, thickness, and separation that result in the best fit. Wallace assumed a pattern of magnetization that varied sinusoidally along the tape but was constant throughout the recorded thickness. It seemed to us that a variation of remanent magnetization with depth would be more in keeping with the profile of the recording head field and the orientation of the magnetic particles in the tape. The argument is illustrated in Fig. 1. The direction of the remanent magnetization acquired by a uniaxial particle after exposure to a field capable of switching it is that easy direction which lies closest to the applied field direction. Thus, in Fig. 1(a), the purpose in applying the field in the direction shown is to switch the remanent magnetization of the particles to that direction. This is accomplished for the particle labeled b, but the one labeled a, as a result of its attitude with respect to the field direction, will acquire a remanence whose in-plane component is opposed to the desired direction. Thus, for particles a and b the vertical components of remanence are additive, but the horizontal (i.e., in-plane) components are subtractive. For the deeper-lying particles, c, d, e, and f, the direction of the flux line has changed enough that their horizontal components of remanence are now additive even though c and e have the same attitudes as a, and f and d have the same as b. As a result, a layer of reduced in-plane magnetization should be found on the portion of the surface of recorded tapes lying closest to the writing head.

This paper describes the results of measurements performed on several tapes of iron oxide particles and chromium dioxide particles. From the measurements we conclude that there is indeed a "dead layer" on the recorded tapes. For the tapes measured, the layer is least serious for oriented particles of CrO_2 and most serious for unoriented particles of γ-Fe_2O_3.

Experimental method

In the first experiment, the head was driven with direct current and used to write on tapes that were initially ac-erased and subsequently determined by a vibrating-sample magnetometer to have a remanent moment ≤ 0.25

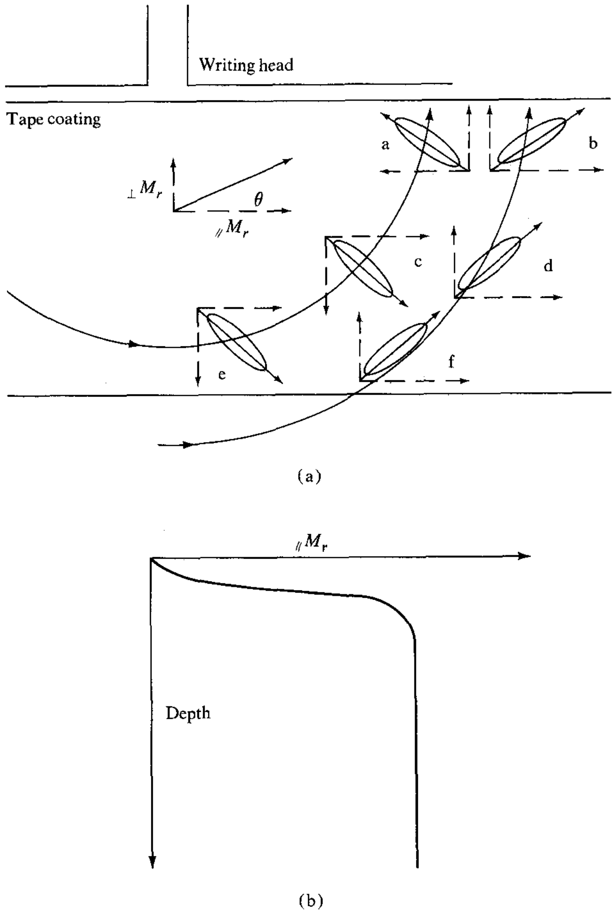

Figure 1 Hypothetical considerations of remanence in a tape coating material. (a) Section-view of the writing head and tape coating, showing the flux lines and the direction of remanence by particles at various attitudes and depths within the coating. (b) The expected distribution of in-plane remanence ${}_{\parallel}M_r$ with depth in the coating.

percent of saturation remanence. The tapes were written on a loop tester in which the velocity was limited to 25 cm/s to ensure contact between head and tape. Both heads used had gaps, which extended the full width of the tape (1.27 cm); thus, after recording, a sample 1.11 cm in diameter could be punched from the tape and measured in the vibrating-sample magnetometer. After the in-plane moment ${}_{\parallel}M_r$ induced by the head was determined, each sample was driven to saturation in a field of 5.33×10^5 amp-turns/meter (6 700 Oe) and the remanence (M_r) was measured. The results were expressed in reduced form (${}_{\parallel}M_r/M_r$) to eliminate sample-to-sample variations caused by differences in coating thickness or in particle loading.

The perpendicular moment, ${}_{\perp}M_r$, cannot be measured accurately on the vibrating sample magnetometer by simply rotating the sample into a vertical plane. Not only is the coupling poor between ${}_{\perp}M_r$ and the detection coils, but a slight misplacement of the sample away from the vertical would lead to the picking up a component of ${}_{\parallel}M_r$ by the coils. The method by which ${}_{\perp}M_r$ was found was to hang the recorded sample, with its plane vertical, in a uniform field of 795 amp-turn/meter (10 Oe) by means of a 25-μm nylon fiber. Because the torsion constant of the suspension is negligible, the sample comes to rest with its plane at an angle θ with the direction of the applied field. Clearly, ${}_{\perp}M_r = {}_{\parallel}M_r \tan \theta$.

In subsequent experiments, which are more appropriately discussed in the next section, the initial state of the samples is one of saturation remanence, obtained by pulling the tape through a solenoid in which the field is 1.19×10^5 amp-turns/meter (1 500 Oe).

Results

The results obtained on four tapes are reported here:

1. An oriented coating of γ-Fe_2O_3 particles,
2. an unoriented coating of γ-Fe_2O_3 particles,
3. an oriented coating of CrO_2 particles, and
4. an unoriented coating of cobalt-substituted γ-Fe_2O_3 particles.

The salient magnetic properties are summarized in Table 1.

The results obtained with the CrO_2 tape by using a 10-μm gap head are shown in Figs. 2 and 3. As the writing current increases, the field penetrates deeper into the coating and ${}_{\parallel}M_r$ increases, reaching a maximum (Fig. 2) at a current of about 35 mA. This maximum has a value of reduced moment (${}_{\parallel}M_r/M_r$) of 0.98; if the current increases, the value of ${}_{\parallel}M_r/M_r$ decreases. Thus, no matter how high a current we pass through the head, we cannot magnetize the tape to saturation remanence. The perpendicular reduced remanence ${}_{\perp}M_r/M_r$, also plotted in Figs. 2 and 3, rises to a plateau of 0.05. If this component is added vectorially to ${}_{\parallel}M_r/M_r$, the resultant vector is only slightly different from ${}_{\parallel}M_r/M_r$. Thus, the difference between ${}_{\parallel}M_r/M_r$ and 1.000 cannot be ascribed to the perpendicular moment; rather, it is the result of a real reduction in ${}_{\parallel}M_r/M_r$ that arises from particles near the surface of the tape being magnetized the "wrong way."

The possibility exists that the distribution of particles in the tape coating might be asymmetrically distributed with respect to the plane of the coating. This effect can be produced by improper arrangement of the orienting magnet and leads to a tape which, when passed by the head in one direction, shows a larger signal than in the other. We determined that this is not the case with our samples by repeating the experiment with the tape reversed, i.e., rotated 180° about an axis normal to the plane of the tape. The result of the reversal is also plotted in Fig. 2 for both ${}_{\parallel}M_r/M_r$ and ${}_{\perp}M_r/M_r$.

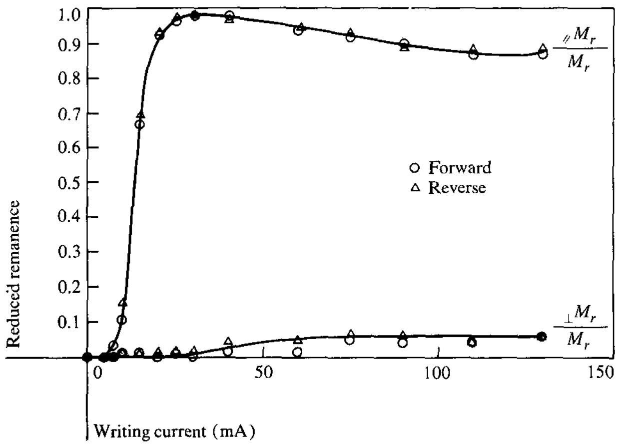

Figure 2 Dependence of the in-plane reduced remanence ($_{||}M_r/M_r$) and the perpendicular reduced remanence ($_{\perp}M_r/M_r$) on writing current for oriented CrO_2 particles initially ac-erased. The write head gap is 10 μm. The points shown by the symbol Δ are obtained by reversing the tape about an axis normal to the plane of the coating.

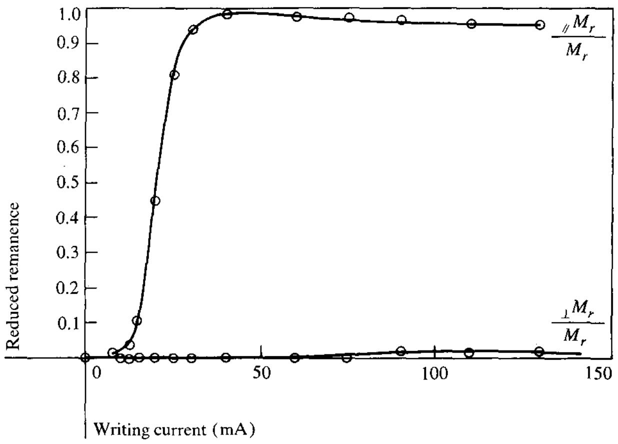

Figure 3 Dependence of the in-plane reduced remanence ($_{||}M_r/M_r$) and the perpendicular reduced remanence ($_{\perp}M_r/M_r$) on writing current for oriented CrO_2 particles. The write head gap is 10μm. A 2.5-μm shim is used between the tape and the head.

Table 1 Magnetic properties of the tapes.

	Oriented γ-Fe_2O_3	*Unoriented* γ-Fe_2O_3	*Oriented* CrO_2	*Unoriented* Co-γ-Fe_2O_3
Saturation magnetization of coating, I_s, weber/meter^2	181	156	207	194
emu/cc	144	124	165	154
Coercivity, H_c, ampere-turns/meter	2.13×10^4	2.03×10^4	3.80×10^4	4.66×10^4
Oersteds	267	255	477	586
Remanence coercivity, H_r, ampere-turns/meter	2.47×10^4	2.50×10^4	3.92×10^4	5.20×10^4
Oersteds	310	314	492	653
Squareness $\frac{I_r}{I_s}$	0.667	0.573	0.83	0.68
Orientation ratio	1.39	1.07	2.52	1.23
Coating thickness in μm	2.5	2.5	3.75	3.80

Table 2 Remanence induced by the head (10-μm gap).

	Unoriented γ-Fe_2O_3		*Oriented* γ-Fe_2O_3		*Oriented* CrO_2		*Unoriented* Co-γ-Fe_2O_3	
	No shim	*shim*	*No shim*	*Shim*	*No shim*	*Shim*	*No shim*	*Shim*
Maximum of $_{||}M_r/M_r$	0.92	0.945	0.95	0.96	0.98	0.985	0.96	0.97
Current for maximum $_{||}M_r/M_r$ (mA)	20	30	20	30	35	40	35	40
Current for maximum low-density output (mA)	22.5	25	30	35	40	45	47	50
Maximum of $_{\perp}M_r/M_r$	0.15	0.12	0.15	0.085	0.05	0.02	0.10	0.07

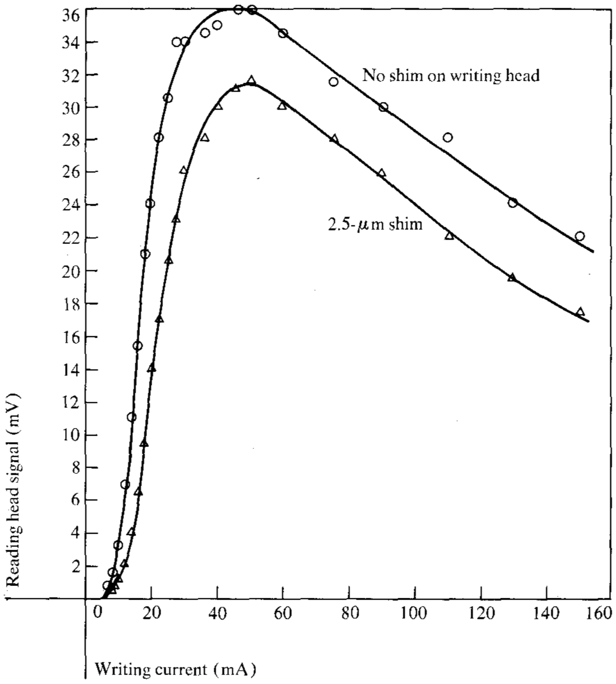

Figure 4 Output of a 1.25μm-gap read head as a function of writing current for an NRZI all-ones pattern at a density of four flux changes per centimeter. The magnetic particles are of cobalt-substituted γ-Fe_2O_3.

Figure 3 presents the results when the experiment was repeated with a nonmagnetic shim 2.5 μm thick between the tape and the head. The principal results of the increased separation between the tape and the head are that the maximum current at which the peak in $_{\parallel}M_r/M_r$ occurred is increased from 35 mA to 40 mA, and the value of the maximum is increased from 0.980 to 0.985. Similar (and larger) increases were found for the other three tapes. This result is not surprising when we remember that spacing the writing head from the tape will alter the distribution of in-plane to perpendicular fields in favor of the in-plane fields and will thus lead to a thinner dead layer. In support of this view, the maximum value of $_{\perp}M_r/M_r$ was decreased by the use of the shim. The effects of the shim for the four tapes are summarized in Table 2.

Figure 4 shows the dependence of the signal output level of a very low density pattern on the write current for the tape made of cobalt-substituted γ-Fe_2O_3 particles. The current at which the output reaches its maximum value is greater when a shim is placed between the head and the tape. This current is also listed in Table 2 for each tape, indicating that there is a close relationship between the current required to produce the maximum value of $_{\parallel}M_r/M_r$ and that needed to give the maximum output signal. Beyond the peak, the output decreases much more rapidly than does $_{\parallel}M_r$.

The next step in the experiment is to repeat the first part with a writing head having a narrower gap (2.25 μm), because the writing performance of the head is known to be affected by this dimension. The results are given in Fig. 5. Comparison of Figs. 2 and 5 shows that the behavior of $_{\parallel}M_r$ to the right of the peak is different for the two gaps. Beyond the peak with the narrower gap we find a decrease in $_{\parallel}M_r$, followed by a second increase that continues steadily to the highest currents and reaches levels that are higher than the initial peak. An explanation of this behavior is given in the next section.

Once more the perpendicular component of magnetization $_{\perp}M_r$ is insufficient to explain the difference between $_{\parallel}M_r/M_r$ and 1.00. The creation of a dead layer on the surface of the recorded tape seemed the most likely explanation of the results, but the interpretation was complicated by the occurrence of two processes at the same time. Starting with a tape that has been ac-erased, and increasing the direct current applied to the head, causes the in-plane magnetization to grow as the field penetrates deeper. However, the dead layer also grows, and the curves of $_{\parallel}M_r/M_r$ show only the sum of these two processes. We have found a more direct way of demonstrating and measuring the dead layer alone, and this technique is now described.

The tapes are first put into the condition of maximum in-plane remanence by being drawn through a solenoid in which a steady field of 1.19×10^5 amp-turns/meter (1 500 Oe) is applied. The tapes are then transferred to the loop tester and moved slowly past the head, which is driven with direct current in a direction such as to support the remanent magnetization of the tape. If only the horizontal component of the writing head field were important in determining the remanent state of the tapes, then clearly we should not expect any change in the remanent magnetization of tapes that were already in the maximum remanent condition. Actually, as is shown by the curves marked "P" in Fig. 5, the remanence at first decreases as the direct current level in the head increases. Furthermore, the decrease is such as to bring the in-plane remanence to a value just slightly above that achieved by writing on an ac-erased tape with direct current ($_{\parallel}M_r$). We believe that this experiment shows directly and unambiguously the existence and the magnitude of the dead layer, which ranges from a minimum of 2 percent (0.075 μm) for the CrO_2 tape to a maximum of 20 percent (0.5 μm) for the tape made of unoriented particles of γ-Fe_2O_3.

To appreciate how the writing field penetrates the coatings as the current in the head is increased, an additional experiment was performed in which the tapes, initially at maximum in-plane remanence, are run slowly past the head, which is being driven by a sinusoidal cur-

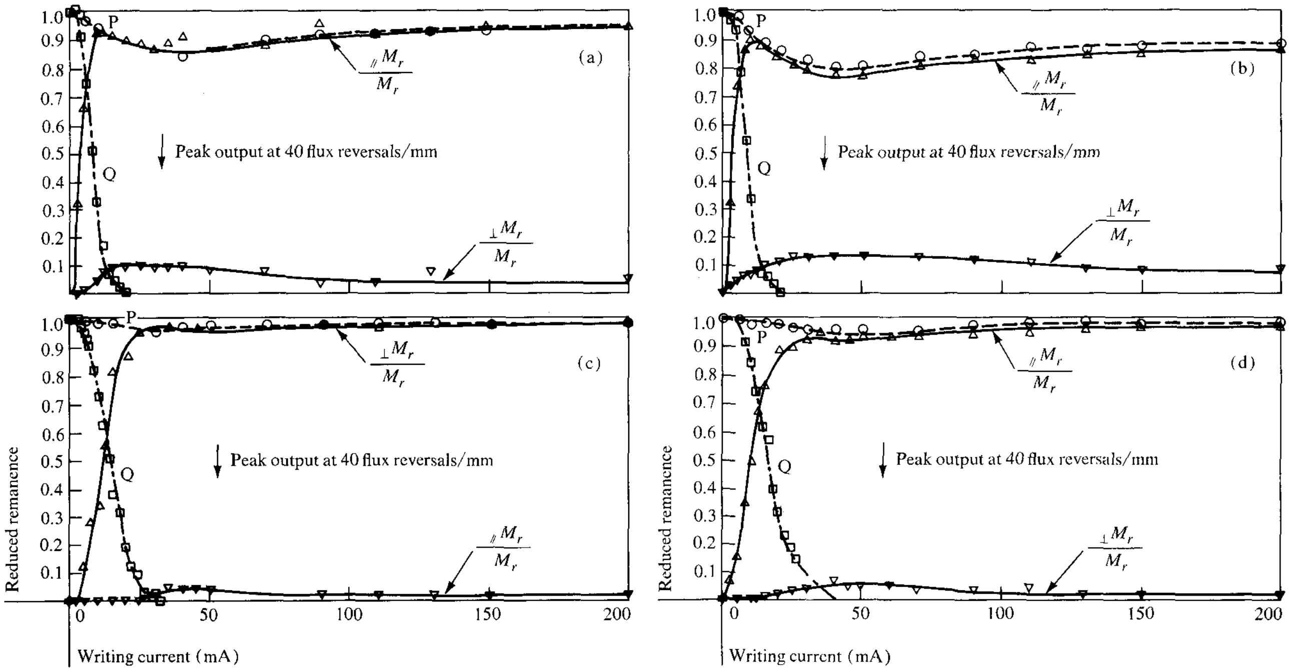

Figure 5 Dependence of $_{||}M_r/M_r$ and $_{\perp}M_r/M_r$ on writing current, for a 2.25-μm gap. *Curve P:* The tape is initially magnetized to maximum in-plane remanence (that is, $_{||}M_r/M_r = 1.00$) and then passed by the writing head, which is driven with direct current so that the horizontal component is in the same direction as the tape magnetization. *Curve Q:* The tape as initially magnetized to maximum in-plane remanence, and then progressively erased by an all-ones pattern at 40 flux changes per millimeter. (a) Oriented particles of γ-Fe_2O_3. (b) Unoriented particles of γ-Fe_2O_3. (c) Oriented particles of CrO_2. (d) Unoriented particles of Co-γ-Fe_2O_3.

rent. The frequency is such that the recorded density on the tape was 40 flux changes per millimeter. The recorded layer thus appears to the magnetometer as a demagnetized layer, and by measuring the decreasing moment of the samples, we are able to follow the penetration of the head field into the tape. The results are shown by curves "Q" in Fig. 5. The initial application of the sinusoidal field ($\leq$3 mA) produces no change in remanence and corresponds to the flux bubble crossing the space between the head and the tape. At the low speeds used in these experiments, the separation is determined by the surface roughnesses of head and tape. For writing currents larger than three mA, the remanence decreases rapidly and linearly. We can, to a first approximation, regard these graphs as showing the movement through the coating of the contour of constant field, $H \approx 2H_r$, since this field is sufficient to switch more than 95 percent of the particles and when this contour reaches the bottom of the coating the tape is then magnetized in stripes of alternating polarity and the net moment is zero.

Beginning with the tapes in the ac-erased condition, we next determine the growth of signal output level from a narrow-gapped reading head after writing on the sample tapes with a sine wave signal at a density of 40 flux reversals per millimeter. The curves show the usual maximum at a value of current shown in Fig. 5. The current required for peak output exceeds by a factor of two to three the current needed to give maximum $_{||}M_r$. Also, it exceeds by a factor of one to two the current needed to drive the $H \approx 2H_r$ contour through the coating.

We give the results of measurements of $_{||}M_r$ and $_{\perp}M_r$ on the four tapes, but so far we have not mentioned the third component of remanent magnetization. This component lies in the plane of the coating but transverse to the long dimension of the tape. The symmetry of the problem suggests that it would be most surprising if this component were not zero. We tested the four tapes and found that to the limit of measurement, ±0.25 percent of M_r, it was indeed zero.

Discussion

The in-plane magnetization increases rapidly from the demagnetized condition and reaches a peak before the contour $H \approx 2H_r$ has completely penetrated the coating. The perpendicular component of the head field has two effects: it produces $_{\perp}M_r$ and, perhaps more importantly, it brings about the formation of a layer of reduced in-plane magnetization (i.e, the dead layer) at the surface of the tape. This "layer" reduces $_{||}M_r$ to the value lower than it would have been if the head field consisted entirely of an in-plane component. With the wide-gap writing head, the continuous decrease in $_{||}M_r$ with increasing writing current occurs because the field lines corresponding to $H = H_r$ have a progressively larger perpendicular component. In the case of the narrow-gap head, ${}_{\|}M_r$ decreases at first and then begins to increase slowly with increasing current. We believe that this slow increase is associated with the saturation of the head pole tips. As the effective permeability of the pole pieces decreases, the flux lines leave and enter the head surface (and, therefore, the tape surface) at angles that deviate more and more from 90° [3, 4]. Then, because the vertical component of the field is reduced, both the dead layer and ${}_{\perp}M_r$ are also reduced, as we have observed.

If we add the magnetization lost in the dead layer (obtained from the application of dc to the head on tapes initially at maximum in-plane remanence) to ${}_{\|}M_r$ (measured from the growth of in-plane remanence after ac erasure) and then add the sum vectorially to ${}_{\perp}M_r$, we arrive at a total reduced moment that is insignificantly different from M_r at any value of writing current beyond the peak of ${}_{\|}M_r$. Thus the writing field produces in the coating an in-plane magnetization that is modified at the surface by the dead layer and by a perpendicular component of magnetization. The latter was never more than about 15 percent of the in-plane component in these experiments, but this value must be regarded as a lower bound to ${}_{\perp}M_r$. Because the writing fields were produced by direct current, the establishment of a perpendicular magnetization will be opposed by demagnetization fields. If the recorded pattern were, say, all-ones NRZI, the macroscopic moment would be zero and a larger perpendicular component would be possible. This component is important because it leads to pulse asymmetry in the readback signal and thus to timing errors.

The small dead layer and ${}_{\perp}M_r$ found for the oriented CrO_2 particles, and the larger effects found for the unoriented γ-Fe_2O_3 particles, are, we believe, largely attributable to the better in-plane orientation of the former. That is, the clean shape of the CrO_2 particles and their highly oriented condition result in a distribution in a longitudinal cross-section of the coating [the sectional drawing in Fig 1(a)] in which the particles lie mainly with their long axes in the plane of the coating. The γ-Fe_2O_3 particles, on the other hand, are imperfectly oriented, and consequently more are to be found with easy axes inclined to the plane of the coating and in an attitude in which they can be affected by the perpendicular component of the head field.

Two methods of minimizing ${}_{\perp}M_r$ and the dead layer suggest themselves. First, the coating should consist of highly oriented acicular particles. The normal orientation process, which is designed to bring the particles into alignment, usually with the long dimension of the tape, should also produce the desired parallelism with the coating plane. Second, if the writing head is deliberately spaced away from the tape, the perpendicular component of the writing field will be reduced relative to the in-plane component and its adverse effects on recording performance will be diminished. An optimum separation exists because, if separation becomes too great, the field gradient will suffer, and with it the sharpness of the written transition.

Clearly, the dead layer leads to an increase in the effective separation between the recorded tape and the reading head; and, if the Wallace relation is used to determine the separation, a value is found that will be greater than the one measured by interferometry. Optical methods measure the geometric separation between the tape and the head, one of which must be a transparent dummy. Recording measurements fitted to the Wallace relation lead to an effective magnetic separation which is the distance between the effective magnetic surface of the head and some level inside the coating. We can roughly describe this level as the bottom of the dead layer. There is, of course, no clear line of demarcation between the dead layer and the region below it in which the head field is predominantly in the plane of the coating.

An in-plane remanence which at first increases with depth in the coating was found by Tjaden and Leyten [5] in experiments on their large-scale model of the magnetic recording process. However, they attributed the difference between the vector sum of ${}_{\|}M_r$ and ${}_{\perp}M_r$ and M_r to a rotation of the field during the recording process. Curves somewhat similar to ours for ${}_{\|}M_r$ as a function of writing current were obtained by Tager, Anisimov and Zhizhnevskaya [6], using two different recording heads and video tape, but the curves did not agree with their large-scale model results and were not discussed in detail.

Conclusions

The perpendicular component of the writing head field acting on an array of uniaxial, single-domain particles produces two undesirable effects at the surface of the tape closest to the head. These are a perpendicular component to the remanent magnetization and a reduction in the in-plane component. The former leads to asymmetry of the readback pulse and the latter to a reduction in the output signal level that will be particularly important at high recording densities.

We have measured these effects for four tapes and found that they are minimized when the magnetic particles are strongly oriented.

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