Advanced Particulate Magnetic Tapes Employing Fine Barium Ferrite Particles

Masahito Oyanagi†, Atsushi Morooka†, Masahiko Mori†, Yuichi Kurihashi‡‡, Toshio Tada†, Osamu Shimizu‡ (member), Hiroyuki Suzuki† and Takeshi Harasawa†

Abstract We have developed advanced magnetic tapes using fine barium ferrite particles. The magnetic particle volume of barium ferrite in the tapes is 1600 nm³. The perpendicular squareness ratio, surface roughness (obtained by optical interferometry), and ten-point average roughness (obtained by atomic force microscopy) of these tapes is 0.87, 0.9 nm, and 27 nm, respectively. The tapes show an areal density of 123 Gb/in², corresponding to a capacity of 220 TB, achieved by a combination of advanced drive technologies.

Keywords: Linear tape system, magnetic recording, barium ferrite, particulates.

1. Introduction

The amount of digital data generated is rapidly increasing because of the burgeoning use of information and communication technology in research, business, and services. Hence, expanding the storage capacity of data storage media is in high demand. Particularly, data centers face major issues with safely storing large amounts of digital data over long periods of time at low costs. Particulate magnetic tapes on linear tape storage systems are widely used for data backup and archival because of their low total cost of ownership (TCO)¹, long-term stability, and high reliability in comparison to hard disk drives. In addition, the future roadmap of tape storage systems expand the cartridge capacity to 120 TB², which is also an important factor for using tapes for data backup and archival.

Fig. 1 shows the capacity trends shown by technical demonstrations of linear tape systems, enterprise-class tape cartridges, and LTO tape cartridges. Since their market launch in early 2000s, the storage capacity of LTO systems has seen a two-fold increase about every two years; however, recently, this trend has slowed down. This is because of the difficulties involved in reducing the particle volume of iron-cobalt-based magnetic metal particles (MPs) usually used in particulate tapes, which has consequently posed limitations to increasing the areal density. Hence, to increase the areal density and expand the cartridge capacity of magnetic tapes, high-density recording studies on tape media using barium ferrite (BaFe) magnetic particles have been carried out. These studies demonstrated an areal density of 6.7 Gb/in², corresponding to a 8 TB cartridge capacity in 2006³, 29.5 Gb/in², corresponding to 35 TB in 2010⁴, and 85.9 Gb/in², corresponding to 154 TB in 2014⁵. Based on these technical demonstrations, tape cartridges with a capacity of up to 10 TB are now available commercially. Hence, the capacity of linear tape systems has been dramatically enhanced by the application of BaFe particles.

We have investigated the development of advanced
BaFe tapes to further accelerate the increase in recording density\(^6\). In this paper, we report the application of BaFe particulate media in tapes, which have demonstrated an areal density of 123 Gb/in\(^2\), corresponding to a capacity of 220 TB in 2015\(^7\).

2. BaFe-based tape technologies

Table 1 shows the properties of BaFe particles prepared for this study. The properties of the experimental tape using these BaFe particles are also shown. For comparison, the properties of commercial BaFe tapes and the latest commercial MP tapes are also shown. For this study, BaFe particles with a particle volume of 1600 nm\(^3\), coercivity (Hc) of 223 kA/m, and saturation magnetization (Ms) of 45 Am\(^2\)/kg were used. The new BaFe tape prepared consisted of an approximately 60-nm-thick magnetic layer, a non-magnetic layer, a substrate film, and a back coat layer. Compared to commercial tapes, the new BaFe tapes showed a high degree of orientation in the perpendicular direction, smooth surface roughness, and low coefficient of friction. In the following sections, we describe the key points in the BaFe particulate media technology, which enabled the achievement of such a significant improvement.

2.1 BaFe magnetic particles

Table 2 compares the BaFe particles with MPs. The iron-cobalt-based magnetic MPs are acicular and the magnetic properties (e.g., Hc) originates from the shape anisotropy. Hence, the magnetic properties of the MPs are strongly influenced by their particle shape and therefore, if the MPs cannot maintain their acicular shape at reduced particle sizes, they no longer function as magnetic particles. In addition, iron-cobalt-based MPs need a passivation layer around each particle to prevent oxidative corrosion. Applying a uniform passivation layer also becomes difficult with MP size reduction. Hence, there are limitations to reducing the MP sizes below that used in the market.

On the other hand, since BaFe magnetic particles are hexagonal platelets with crystalline anisotropy, the magnetic properties of the BaFe particles are not influenced by their shape. Furthermore, since the BaFe particles are oxides, a passivation layer is not required. Therefore, the BaFe particle size can be potentially reduced without degrading their magnetic properties.

Fig. 2 shows the dependence of Hc on particle volume for BaFe particles and MPs. The particle volume is an average value calculated from the particle shape observed in a transmission electron microscope (TEM) and Hc is measured using a vibrating sample magnetometer (VSM). The Hc of the BaFe particles can
be controlled by changing their composition by altering the type or amount of the substitution element. Hence, there are several kinds of particles with different Hc values at the same particle volume. Currently, BaFe particles with a particle volume of 1950 nm$^3$ are commercially used; however, we have successfully developed BaFe particles with a particle volume of approximately 1000 nm$^3$ with sufficient Hc. On the other hand, the Hc values of the MPs drastically degrade with reduction in particle volume to values < 2500 nm$^3$. Hence, the areal density can definitely not be improved with MPs.

Fig. 3 compares the degradation in Ms of BaFe particles and MPs as a function of the particle volume at 60°C and 90 RH% over 30 days. The Ms of the MPs drastically degraded with reduction in particle volume. Hence, MPs no longer function as magnetic particles when their particle size reduced. In contrast, the Ms of the BaFe particles hardly degrades with reduction in particle volume. Thus, BaFe particles are very stable even in such a harsh environment. This is an important aspect to be considered for data storage media to be used for backup and archival over a long period of time.

Fig. 4 shows the TEM images of the most recent magnetic (a) BaFe particles (used for the latest technical demonstration) and (b) MPs. The BaFe particles show a volume of 1600 nm$^3$ and Hc of 223 kA/m. In contrast, the MPs show a volume of 2830 nm$^3$ and Hc of 189 kA/m. The BaFe particles are approximately 43% smaller than the MPs; however, the BaFe particles show a higher Hc.

Fig. 5 shows the scanning electron microscopy (SEM) images of the surfaces of the magnetic (a) BaFe tape used for the latest technical demonstration and (b) the latest MP tape. In the BaFe tape, the magnetic particles are dispersed uniformly in high density on the tape surface compared to the MP tape. Thus, the BaFe tape is a more appropriate medium for high-density recording than the MP tape.

2.2 Perpendicular orientation technology

An important technology to enhance the recording performance is controlling the orientation uniformity of the magnetic particles in the magnetic layer. In the MP tape, the MPs are acicular with the easy axis of magnetization aligned in parallel to their longer axis; therefore, they are generally oriented in the longitudinal direction during the coating process. In contrast, since in the BaFe particles, the easy axis of magnetization is aligned perpendicular to the platelet surface, the particles can be oriented in a direction perpendicular to the magnetic layer. The effect of the perpendicular orientation of the BaFe particles is reported in reference (8). This perpendicular orientation enables achieving a remarkable enhancement in the signal-to-noise ratio (SNR).

Fig. 6 shows the cross sectional TEM images of the magnetic layer of the (a) new and (b) commercial BaFe
tapes and (c) the latest MP tape. We have successfully prepared highly perpendicularly oriented BaFe tapes in comparison to the non-oriented commercial BaFe tapes. As shown in these figures, the BaFe particles on the new BaFe tape are better oriented in the perpendicular direction than in the commercial BaFe tapes.

Fig. 7 shows the magnetic hysteresis loop of the new BaFe and commercial BaFe tapes and the latest MP tape. These curves were obtained using VSM by applying an external magnetic field of 1.5 T in a direction perpendicular to the BaFe tapes and in a direction longitudinal to the MP tape. As also shown in Table 1, the perpendicular squareness ratio (SQ) of the new BaFe tape improved to 0.87 from a value of 0.66 shown by the commercial BaFe tape. This value is equal to or greater than that shown by the MP tapes in the longitudinal direction.

2.3 Designing surface smoothness

To improve the recording performance, it is also essential to reduce the head-media spacing. For this, the surface roughness of the magnetic layer needs to be minimal. The surface roughness of the magnetic layer strongly depends on the smoothness of the underlayer and substrate film. Therefore, designing the surface smoothness of the underlayer and substrate film is important. In this study, to reduce surface roughness, a new smooth underlayer was prepared by using finer non-magnetic particles and a new dispersant in the underlayer coating solution.

Fig. 8 shows the surface profile images (measured by optical interferometry) of the (a) new BaFe tape, (b) commercial BaFe tape, and (c) the latest MP tape. This analysis was performed with a sample area of 170 µm × 236 µm to observe relatively long-range surface roughness. As shown in these images, by removing long-range roughness with a wavelength of a few tens of microns, the surface profile of the new BaFe tape is significantly smoother than that of the commercial tapes.

Meanwhile, it is known that the runability of the tape against the magnetic head worsens with reduction in the surface roughness of the magnetic layer because of an increase in the real contact area between the head and the tape. To solve this issue, it is important to control the microscopic surface profile to reduce the real contact area between the head and the tape. For this, we investigated the design of filler particles, which are included in the magnetic layer.

Fig. 9 shows the surface profile images obtained by atomic force microscopy (AFM) of the (a) new and (b) commercial BaFe tapes and (c) the latest MP tape. The AFM analysis was performed on a sample area of 40 _m2 to observe the short-range surface roughness.
shown in the figure, in the new BaFe tape, a large number of surface asperities exist on the tape surface, although a low surface roughness (Ra) and ten-point average roughness (Rz) is maintained. Hence, low friction can be achieved, while maintaining a smooth surface by reducing the real contact area. As shown in Table 1, although the surface of the new tape is smoother than the commercial tapes, the coefficient of friction of the new BaFe tape is 0.21 in comparison to 0.44 for the commercial BaFe tape.

3. Recording performance

The recording performance of the new and commercial BaFe tapes (LTO7) was evaluated using a loop tester at a linear velocity of 2 m/s with an enhanced field tape write head (described in reference (5)), consisting of conventional Ni_{45}Fe_{55} poles with an additional 200-nm-thick liner layer of CoFe deposited between the write gap and the trailing pole, and a giant magnetoresistive head. The broad-band SNR was calculated from the root mean square voltage of the read-back signal corresponding to a written data pattern of period of 2T (where T is the channel bit period) and the noise, which was the integral value of the power spectral density from 0 to 1/T Hz, as measured with a spectrum analyzer.

Fig. 10 shows the dependence of the 2T output as a function of the recording linear density of the new and commercial BaFe tapes. The new BaFe tape shows a higher output and a better frequency response than the commercial tape. The higher output of the new tape is attributed to both the high degree of perpendicular orientation (with a perpendicular SQ of 0.87 in comparison to a value of 0.66 shown by the commercial tape) and a surface roughness reduction with an Ra of 0.9 nm and Rz of 27 nm measured by optical interferometry and AFM, respectively (in comparison to 2.0 nm and 34 nm, respectively, shown by the commercial BaFe tape).

Fig. 11 shows the signal and modulation noise spectrum at a linear density of 340 kfcf (kfcf = × 1000 flux changes per inch). The noise level of the new tape is much lower than that of the commercial BaFe tape. Such a lower noise of the new tape is primarily thought to result from the magnetic particle volume reduction from 1950 nm³ to 1600 nm³.

4. Conclusions

The authors report the development of an advanced BaFe particulate tape enhanced by fine BaFe particles with a particle volume of 1600 nm³, a high degree of perpendicular orientation (with a perpendicular SQ of 0.87), and precisely controlled surface smoothness (long-range roughness, represented by Ra = 0.9 nm, as measured by optical interferometry and short-range roughness, represented by Rz = 27 nm, as measured by AFM). This new BaFe tape achieved a higher output and lower noise compared to the currently available commercial tape and demonstrated an areal recording density of 123 Gbit/in², corresponding to 220 TB achieved in combination with newly developed tape drive technologies.

Furthermore, we also developed BaFe particles with a particle volume of 1000 nm³; therefore, we believe that tapes using BaFe particles can be used to continue enhancing the recording capacity at a low TCO in long-term future.

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Masahito Oyanagi received B.E. and M.E. degrees in Condensed Matter Physics from the University of Tsukuba in 2000 and 2002, respectively. He is a research engineer at the Recording Media Research Laboratories, FUJIFILM Corporation. His current interest is the development of high-density particulate tapes using BaFe particles.

Atsushi Morooka received his B.E. degree in reaction physical chemistry from Hiroshima University in 2003 and M.E. degree in biomolecular chemistry from Osaka University in 2005. He is working as a research engineer at the Recording Media Research Laboratories, FUJIFILM Corporation. His current interest is the development of high-density particulate tapes using BaFe particles.

Masahiko Mori received B.E. and M.E. degrees in applied chemistry from Keio University in 1993 and 1995, respectively. He is a research engineer at the Recording Media Research Laboratories, FUJIFILM Corporation.

Yuichi Kurihashi received B.E. and M.E. degrees in electrical and electronic engineering from Tohoku University in 2007 and 2009, respectively. He works in the Recording Media Products Division, FUJIFILM Corporation.

Toshio Tada received B.E. and M.E. degrees in applied chemistry from Osaka University in 2003 and 2005, respectively. He is a research engineer at the Recording Media Research Laboratories, Fujifilm Corporation.

Osamu Shimizu received B.E. and M.E. degrees in Material Science from the University of Electro Communications in 1983 and 1985, respectively. He received his Ph.D from Ibaraki university in 2012. Since 1985, he has been with FUJIFILM Corporation and is engaged in the research of magnetic recording. He is a Senior Member of IEEE. His current research interest is the development of magnetic recording media BaFe particles.

Hiroyuki Suzuki received his B.E. degree in Chemical Biotechnology from the University of Yamanashi in 1993. He is a research manager at the Recording Media Research Laboratories, FUJIFILM Corporation. His current interest is the development of ultrafine BaFe particles.

Takeshi Harasawa received B.E. and M.E. degrees in Nuclear Physics from Niigata University in 1989 and 1991, respectively. He is a research manager at the Recording Media Research Laboratories, FUJIFILM Corporation.

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