Advanced Magnetic Tape Technology for Linear Tape Systems

Barium ferrite technology beyond the limitation of metal particulate media

Osamu Shimizu, Takeshi Harasawa, and Hitoshi Noguchi
Recording Media Research Laboratories
FUJIFILM Corporation
Odawara, Kanagawa, Japan
{osamu.shimizu, takeshi.harasawa, hitoshi.noguchi}@fujifilm.com

***Abstract*—We surveyed the history of using metal particulate media in linear tape systems to enhance cartridge capacity, discussed the metal particulate media limitations, and introduced advanced barium-ferrite-particulate-media-based magnetic tape technology, focusing on the use of magnetic particles, surface profile design, and particle orientation control. The increase in cartridge capacity has been accelerated by combining barium ferrite particles with ultrathin layer coating technology and by controlling the barium ferrite particle orientation and surface asperities, which reduce the surface frictional force without increasing the head-to-media spacing.**

Keywords—linear tape system; barium ferrite; magnetic recording; archive

I. Introduction

Particulate-media-based tape storage systems are widely used for data-backup and archiving applications because of their low-cost, the stability of the recording media for long-term data retention, and the reliability of information retrieval and reproduction. The total worldwide volume of digital data is increasing at an explosive pace and is projected to reach 40 zettabytes (ZB) by 2020: 50 times the volume of data estimated for 2010 [1], implying that the capacity of linear tape systems is expected to grow at a similar pace. Fig. 1 presents the capacity trends of the technical demonstrations of the linear tape system, enterprise-class tape cartridge, linear tape-open (LTO) tape cartridge, and 3.5-inch form factor hard disk drive (HDD). The tape cartridge capacity of products has shown a trend very similar to that of HDDs while the technical demonstrations of the linear tape systems have shown trends far beyond those of the products. One-terabyte (TB) cartridge technical demonstration [2], corresponding to an areal recording density of approximately 1 Gbit/in^2, was achieved with metal particulate (MP) tape media in 2003, and 1-TB MP cartridges were commercially launched in 2008. The first and second barium ferrite (BF) tapes (*i.e.*, BF-1st and -2nd) technically demonstrated 6.7 and 29.5 Gbit/in^2 in 2006 [3] and 2010 [4], corresponding to 8 and 35 TB per cartridge, respectively. Nowadays, 2.5- to 8.5-TB BF tape cartridges are commercially produced using the same technology as that used for BF-1st. Products up to 30 to 40 TB per cartridge commercially produced using the same technology as that used for BF-2nd will soon be available. Technical demonstration beyond 100 TB per cartridge is also expected to be achieved very soon [5]. This paper discusses the details of the key technologies used to enhance the cartridge capacities of linear tape systems. Table I lists the key items, which enhance the cartridge capacities of magnetic tape media. In the next section, we first survey the history of increasing MP media capacity, focusing on the aspects listed in Table I, which will be followed by a discussion of MP media limitations. The details of the BF technologies used to overcome MP media limitations are introduced in section III.

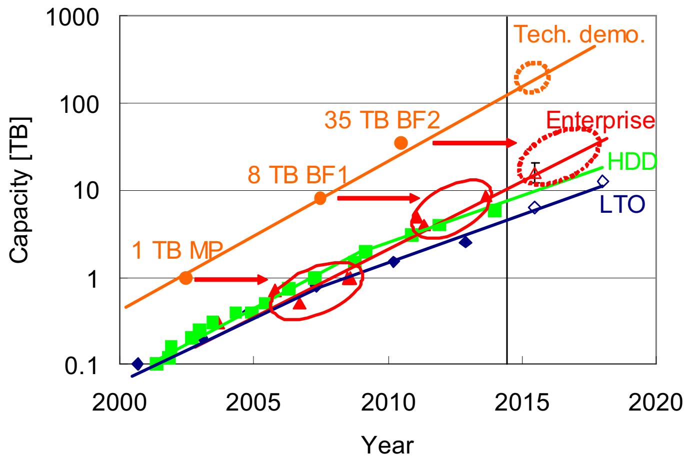


Fig. 1. Capacity trends for technical demonstration of linear tape system (orange), enterprise-class tape cartridge (red), LTO tape cartridge (dark blue), and 3.5-inch form factor hard disk drive (light green).

TABLE I KEY ITEMS FOR ACHIEVING HIGH-CAPACITY MEDIA

	Item	Advantage	Risk
a	Small magnetic particles	High SNR	Loss of magnetic properties
b	Thin magnetic layer	High resolution	Coating uniformity
c	Smooth surface profile	Low spacing	Friction between tape and head
d	Thiner tape	Longer tape (High Capacity)	Strength of tape media

II. Metal Particulate Media

The capacities of MP tape cartridges have been increased by decreasing (a) the magnetic particle volume without degrading magnetic properties such as coercivity and magnetic moment, (b) the magnetic layer thickness, (c) the medium surface roughness, and (d) the total tape thickness. In this

978-1-4799-5671-5/14/$31.00 ©2014 IEEE

section, the history of increasing MP tape cartridge capacity is surveyed from these four perspectives and the MP media capacity limitation is then discussed.

A. Magnetic Particles

Magnetic particles are one of the most important aspects of recording media. Small magnetic particles are essential for reducing noise, resulting in a high signal-to-noise ratio (SNR) adequate for reproducing the signal as error-free data. Halving the particle volume corresponds to increasing the SNR by 3 dB, which could narrow the reader track by one-half. Fig. 2 shows the reduction in MP media particle volume over time. In the 1990s, the volume of particles used in MP media was more than 100,000 nm^3 while that of those used in the latest MP media is less than 3,000 nm^3.

B. Magnetic Layer Thickness

In longitudinal magnetic recording, which is used in MP media, the thickness of the magnetic recording layer should be controlled on the order of ~$\lambda/4$, where λ represents the wavelength of the recorded signal and is proportional to the bit length or inversely proportional to the linear density. Even if the magnetic layer was thicker than $\lambda/4$, the signal barely increases whereas the noise increases thereby decreasing the SNR. Fig. 3 shows the magnetic layer thickness trends over time. They drastically changed twice. The first time was in the mid-90s and second in 2010. The first and second thickness reductions were achieved using ATOMM [6]-[8] and NANOCUBIC [9] technologies, respectively. Fig. 4 shows the cross-sectional views of MP media produced using ATOMM and NANOCUBIC technologies. The interface boundary between the under and magnetic layers of the MP medium produced using NANOCUBIC technology appears much smoother than that between the ones of the MP medium produced using ATOMM technology, which could enable us to reduce the magnetic layer thickness to 60 nm or thinner.

C. Surface Roughness

The spacing between the head and the medium (d) decreases the signal output, especially in the high linear density region (*i. e.*, when λ is small), $Signal \propto -54.6d/\lambda[dB]$. This formula shows that a spacing one-tenth as wide as the wavelength (for example, d = 5 nm when λ = 50 nm) approximately halves the signal amplitude. The medium surface must be as smooth as possible while suppressing the frictional force low enough to maintain high runability, which is required for reliability, in order to minimize the spacing between the head and the medium. Fig. 5 presents the reduction of surface roughness in MP. In the 1990s, the surface roughness of MP media was approx. 7 nm in R_a (centerline average roughness), while that of the latest MP media is less than 3 nm. Fig. 6 shows the significant difference between the surface roughnesses of the LTO-1 and LTO-5 produced using ATOMM and NANOCUBIC technologies, respectively.

D. Total media thickness

Cartridge capacity is not only a function of areal density but also of tape length. Reducing the total tape thickness

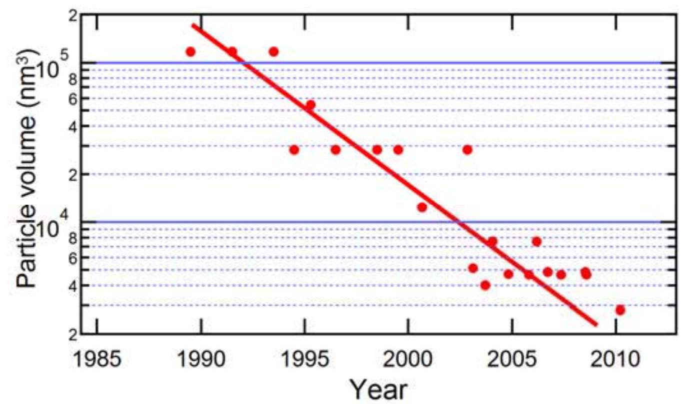


Fig. 2. Change in metal particle volume over time.

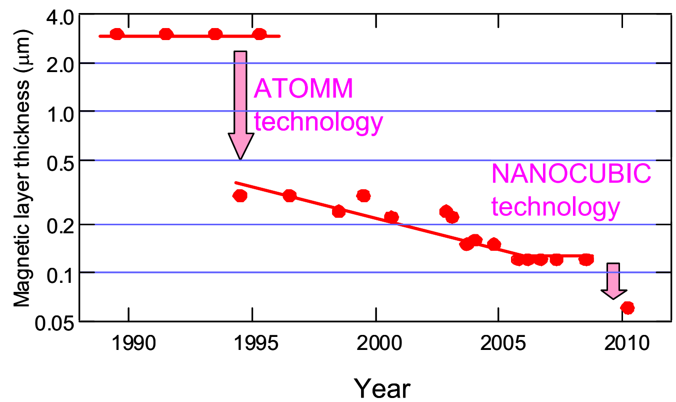


Fig. 3. MP media magnetic layer thickness. ATOMM technology reduced magnetic layer thickness to submicrometer level and NANOCUBIC technology reduced it to several tens of nanometers.

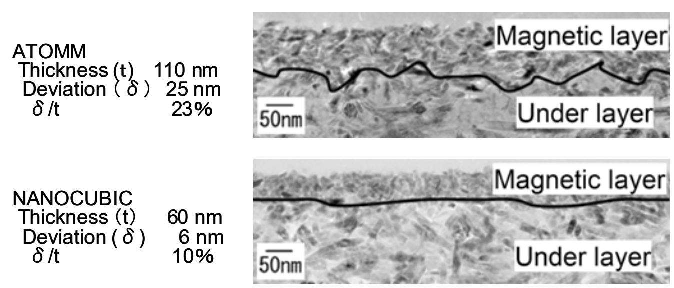


Fig. 4. Comparison of media produced using ATOMM and NANOCUBIC technologies. Deviation in interface between nonmagnetic under layer and magnetic layer was reduced to 6 nm using NANOCUBIC technology.

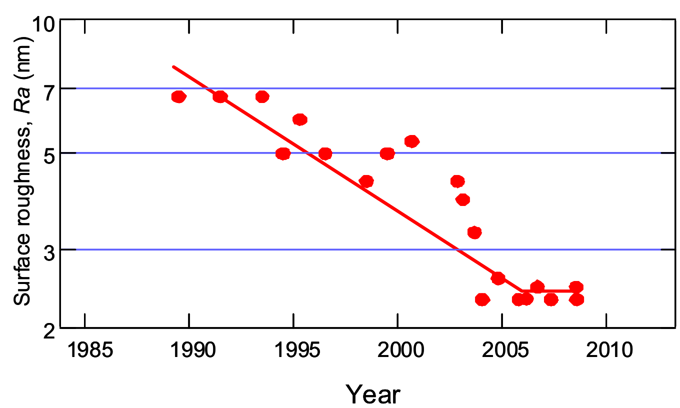


Fig. 5. Reduction in MP tape surface roughness.

enables a longer tape to be stored in the same size cartridge; thus, three-dimensionally increasing the cartridge capacity. As shown in Fig. 7, the tape thickness has been reduced by approximately one-third in the past 20 years, which has contributed to a 3-fold increase in capacity.

E. Limitaion of MP

Although the half-inch-wide tape-media cartridge used 30 years ago was able to store 0.1 GB per cartridge (Digital Equipment Corporation (DEC), TK50 with CompacTape I), the latest MP cartridge (LTO-6) can record up to 2.5 TB per cartridge without compression, corresponding to an average annual growth of 40%. However, 2.5-TB LTO-6 was launched nearly three years after launching 1.5-TB LTO-5, indicating that the speed at which the capacity of the MP-based cartridge had increased was apparently reduced. In addition, the metal particles used in LTO-6 are "essentially identical" to those used in LTO-5 [10]. These facts imply that there will be no future margin for enhancing the capacity of MP-based cartridges. One of the important technologies used to enhance cartridge capacity until 2010 (LTO-5) was to reduce the magnetic particle volume. Capacity increase saturation reflects the difficulty in continually reducing metal particle volume while maintaining sufficient magnetic properties such as coercivity and saturation magnetization, because MP media coercivity depends on shape anisotropy and because each particle surface must be covered with a passivation layer consisting of a material showing much lower saturation magnetization, which places a severe practical limit on the minimum particle volume. Fig. 8 shows the dependence of coercivity on MP particle volume. Decreasing the particle volume less than 3,000 nm^3 drastically decreases coercivity, which seems to restrict the use of smaller metal particles in LTO-6 compared to LTO-5.

III. BARIUM-FERRITE MEDIA

Intensive research on evaporating metal [11][12], sputtering thin films on flexible base substrates [13]-[17], and using iron nitride [18][19] and barium ferrite [20]-[30] particles has been conducted to increase the capacities of MP media in linear tape systems. Although many attempts to develop alternatives have been made, only BF technology has continually demonstrated system-level reliability and was finally marketed. The superior properties of BF media is surveyed and BF and MP media are compared in this section.

A. Barium Ferrrite Particles

A comparison of metal and barium ferrite particles is listed in Table II. Unpassivated Fe-Co alloy particles are unstable in the air because metal powder is easily oxidized whereas barium ferrite is essentially stable because it is an oxide. The ratio of the long to short axes of acicular metal particles must be maintained because metal particle shape induces magnetic anisotropy (*i.e.*, shape anisotropy), which is the origin of metal particle magnetic coercivity, whereas the shape of barium ferrite particles can be controlled without concerning their coercivity because magnetocrystalline anisotropy induces the magnetic anisotropy of barium ferrite particles, and their shapes are not the dominant factor. As a result, platelet-shaped

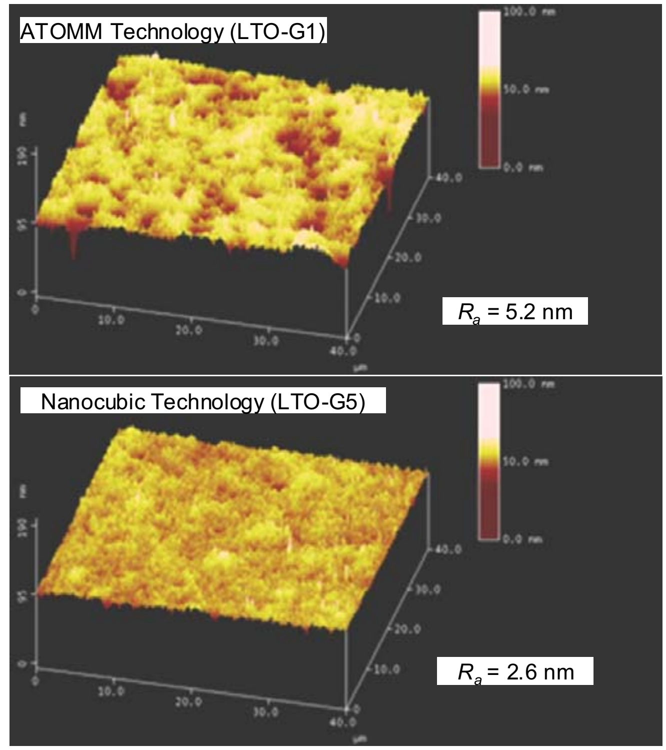


Fig. 6. Profiles of LTO-1 and LTO-5 surfaces produced using ATOMM and Nanocubic Technologies, respectively. Surface roughness (*R*a) of LTO-5 is only 2.6 nm while that of LTO-1 is 5.2 nm.

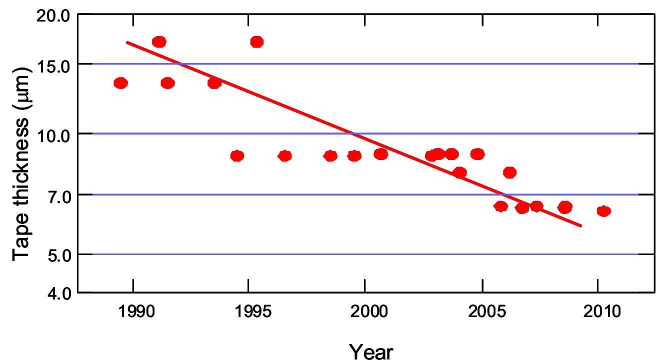


Fig. 7. Tape thickness trends over time. Total tape thickness consists of substrate and back, under, and magnetic layer thicknesses and has decreased from 17 to 6 μm in last 30 years

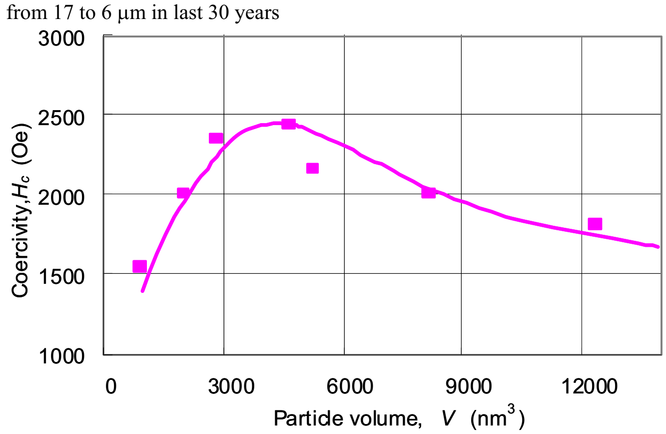


Fig. 8. Dependence of coercivity on particle volume. Metal particles whose volumes are <3,000 nm^3 cannot maintain their magnetic properties, so drastically coercivity decreases.

particles whose easy axis is perpendicular to their plane could be used, which is advantageous for coating perpendicularly oriented media.

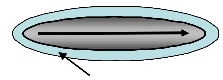
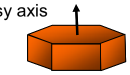
Fig. 9 presents the tunneling electron microscopy (TEM) image of the metal particles used in the LTO-5, which were the smallest metal particles that maintained their magnetic properties, and the barium ferrite particles used in the BF-2nd (*i.e.*, 29.5 Gbit/in^2) demonstrations. The barium ferrite particles used in the BF-2nd demonstration were as small as 1,600 nm^3, and they maintained a coercivity as high as 2,550 [Oe]. The barium ferrite particle volume limitation may come from their thermal stability, which is considered to be <1,000 nm^3. The 128-TB cartridge expected to be launch in 2020 according to the INSIC roadmap 2012 [31] will use ~1,029-nm^3 particles.

The scanning electron microscopy (SEM) images of the LTO-5 and BF-2nd surfaces are shown in Fig. 10. The barium ferrite particles (BF-2nd) are densely packed and relatively uniformly sized, while the metal particles (LTO-5) are not densely packed and show considerable variation in volume and some variation in orientation.

B. *Surface Profile design*

The surface of the medium should be as smooth as possible to minimize the head-to-medium spacing. However, the fundamental dilemma in contact magnetic recording is that increasing the medium smoothness may increase the amount of friction and, hence, may decrease the medium durability and runability. To resolve this dilemma, we reduced the long-range surface roughness, which we refer to as "waviness," while adding asperities to maintain a moderate short-range one. Fig. 11 presents the conceptual profiles of the "wavy" and "asperous" surfaces. The asperous surface, unlike the wavy one, reduced the spacing without runability loss. Fig. 12 shows the profiles of the LTO-5, BF-1st, and BF-2nd surfaces measured using optical interferometry and atomic force microscopy (AFM) over 180 μm × 240 μm and 40 μm × 40 μm areas, respectively. The data measured using optical interferometry show a waviness of Ra = 0.7, 2.0, and 2.0 nm for the BF-2nd, LTO-5, and BF-1st surfaces, respectively. Note that the AFM image of the BF-2nd surface shows many more small asperities than the AFM images of the LTO-5 and BF-1st ones. The combination of the low BF-2nd surface waviness and the

TABLE II COMPARISON OF MP AND BF

	Metal particle	Barium ferrite particle
Shape	 Acicular	 Hexagonal-platelet-shaped
Origin of magnetic energy	Shape anisotropy	Magnetocrystalline anisotropy
Material	Fe-Co alloy	BaO(Fe2O3)6 Oxide
Passivation layer	Required	Not required

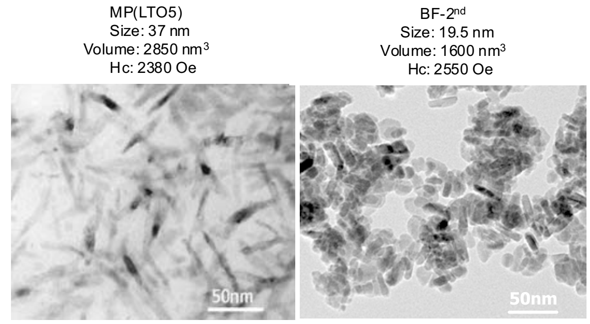


Fig. 9. TEM images of latest MP and barium ferrite particles used in technical demonstration of BF-1st and BF-2nd.

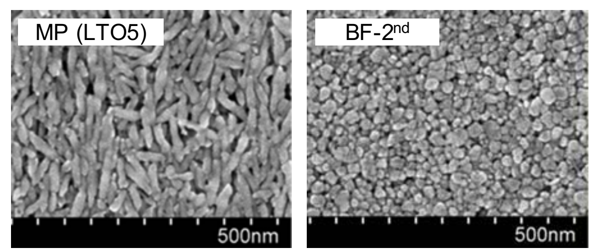


Fig. 10. SEM images of MP and BF magnetic media surfaces.

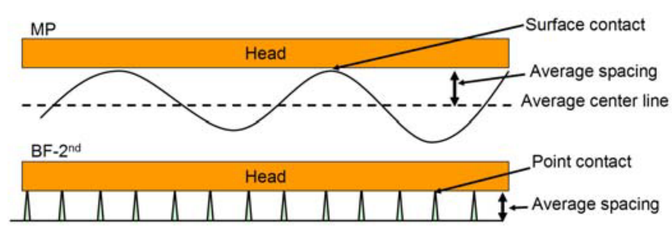


Fig. 11. Conceptual view of balancing competing goals of narrow spacing and low friction.

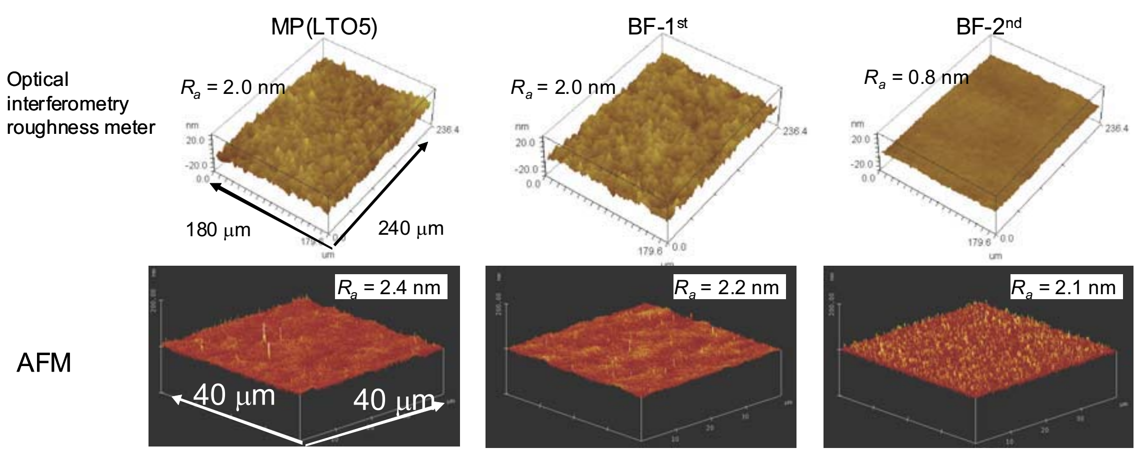


Fig. 12. Profiles of surfaces measured using optical interferometry and atomic force microscopy.

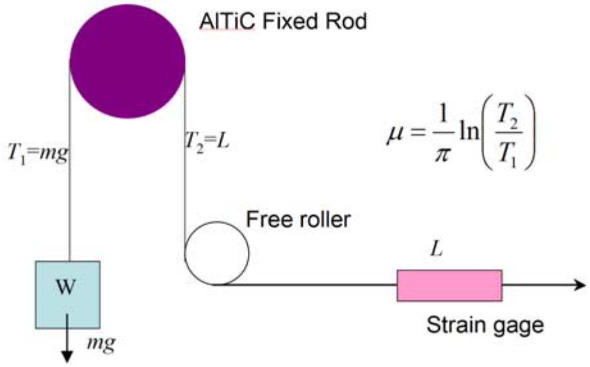


Fig. 13. Method of measuring coefficient of friction. AlTiC rod was used and tape speed was set at 14 mm/s.

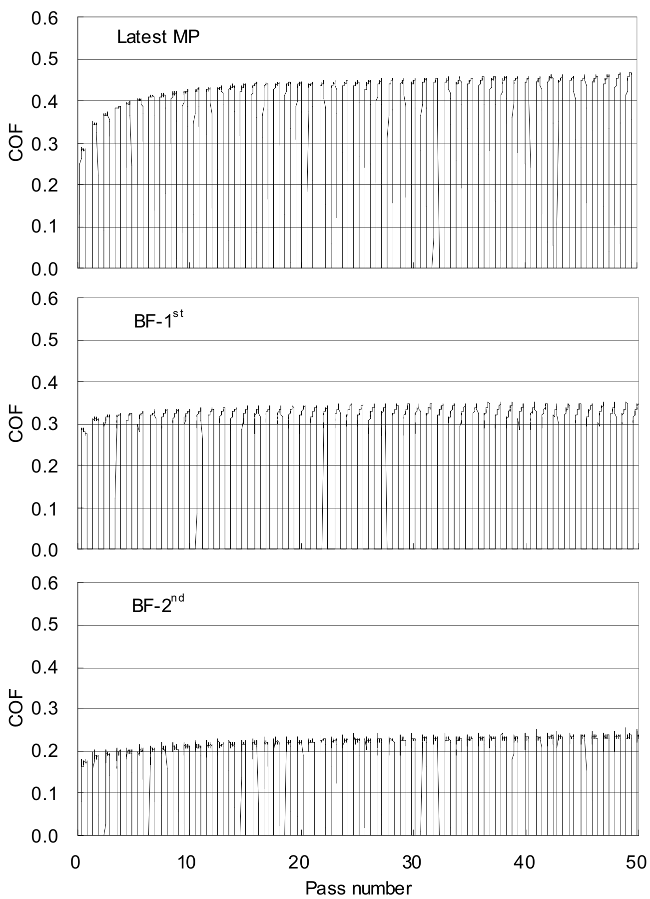


Fig. 14. COFs for LTO-5, BF-1st, and BF-2nd surfaces measured using apparatus shown in Fig. 13.

moderate short-range roughness increased the signal intensity emanating from the medium while maintaining excellent durability and runability. Figs. 13 and 14 present the apparatus used to measure the coefficient of friction (COF) and the COFs measured for the LTO-5, BF-1st, and BF-2nd surfaces, respectively. The COF of the BF-2nd surface was apparently the lowest. Why the COF of the BF-1st surface is lower than that of the LTO-5 one is unclear. However the COFs of BF media are often lower than those of MP media even if their surface profiles are not significantly different. Fig. 15 presents the relation between the COF and surface roughness, *R*a. All four samples are sold as LTO-6 media, and we obtained them

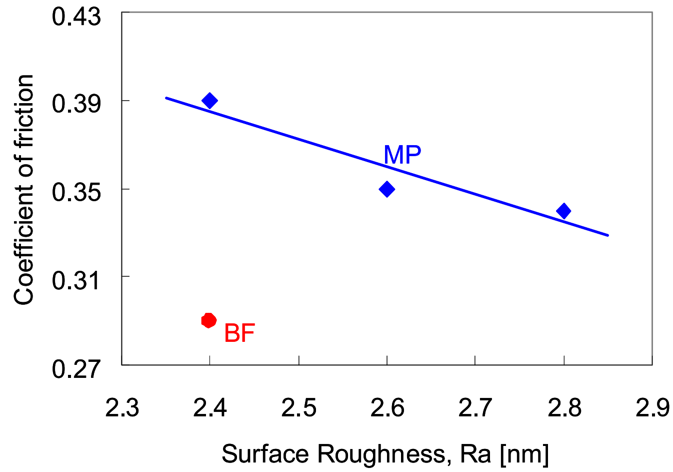


Fig. 15. COF plotted as function of surface roughness.

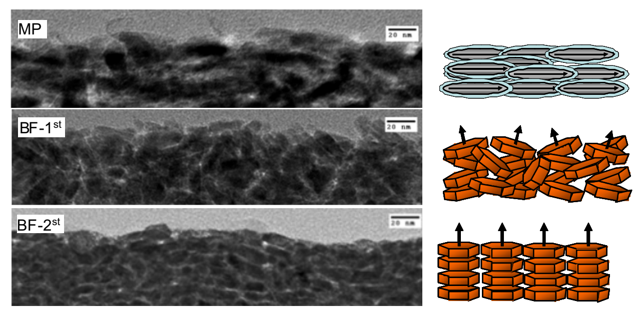


Fig. 16. Cross-sectional views of MP and BF surfaces

on the market. One sample was a BF medium produced using the same technology used for the BF-1st and the other three were MP media. The COF of the BF medium was the lowest even though its surface was the smoothest.

C. Orientation of barium ferrite particles

Fig. 16 presents the cross-sectional views of MP, BF-1st, and BF-2nd magnetic layers. The barium ferrite particles on the BF-2nd surface were highly perpendicularly oriented by applying a magnetic field in the drying zone during coating. While barium ferrite particles on the BF-1st surface were coated without applying a magnetic field in drying zone, we could see somewhat oriented particles due to their platelet shape. Although MP was also coated while applying a magnetic field, the direction of the magnetic field was not perpendicular but longitudinal. Although acicular metal particles can never align their easy axis to the perpendicular direction because of their shape, platelet-shaped barium ferrite particles can easily align their easy axis to the perpendicular direction, resulting in high performance in the high recording density region just like the hard disk drive that showed enhanced areal density by introducing the perpendicular magnetic recording technology.

IV. Summary

We first surveyed the history of the increasing capacity of MP media cartridges in linear tape systems. Although the capacities of MP media cartridges have increased 25,000-fold in the last 30 years, we cannot expect a similar trend in the future because the volume of metal particles, which should be smaller for higher-density recording, cannot be further reduced without sacrificing their magnetic properties. Instead, BF media are expected to replace MP media and continue to rather quickly increase the storage capacity because the volume of BF particles can be reduced to <1,000 nm^3 and because perpendicularly oriented media are easily obtained. BF media can be produced on the same production line as MP media because BF media, just as MP media, are coated under ordinary atmospheric conditions in contrast to vapor- or sputter-deposited media, which require the use of a vacuum apparatus. As a result, the obstacles toward mass producing storage devices are relatively small, and requirement of the explosive amount of worldwide information could be satisfied using BF media.

REFERENCES

[1] John Gantz and David Reinsel, "THE DIGITAL UNIVERSE IN 2020: Big Data, Bigger Digital Shadows, and Biggest Growth in the Far East," http://idcdocserv.com/1414, Dec 2012.

[2] E. R. Childers, W. Imaio, J. H. Eaton, G. A. Jaquette, P. V. Koeppe, and D. J. Hellman, "Six orders of magnitude in linear tape technology: Oneterabyte project," IBM J. Res. Develop. vol. 47, pp. 471–482, 2003.

[3] D. Berman, R. Biskeborn, N. Bui, E. Childers, R. D. Cideciyan, W. Dyer, E. Eleftheriou, D. Hellman, R. Hutchins, W. Imaino, G. Jaquette, J. Jelitto, P.-O. Jubert, C. Lo, G. McClelland, S. Narayan, S. Oelcer, T. Topuria, T. Harasawa, A. Hashimoto, T. Nagata, H. Ohtsu, and S. Saito., "6.7 Gb/in2 Recording Areal Density on Barium Ferrite Tape," IEEE Trans. Magn. vol. 43, no. 8, pp. 3502–3508, 2007.

[4] G. Cherubini, R. D. Cideciyan, L. Dellmann, E. Eleftheriou, W. Haeberle, J. Jelitto, V. Kartik, M. A. Lantz, S. Ölçer, A. Pantazi, H. E. Rothuizen, D. Berman, W. Imaino, P-O. Jubert, G. McClelland, P. V. Koeppe, K. Tsuruta, T. Harasawa, Y. Murata, A. Musha, H. Noguchi, H. Ohtsu, O. Shimizu, and R. Suzuki, "29.5-Gb/in2 Recording Areal Density on Barium Ferrite Tape," IEEE Trans. Magn. vol. 47, no. 1, pp. 137–147, 2011.

[5] M. A. Lantz and E. Elefteriou, "Future Scaling Potential of Particulate Media in Magnetic Tape Recording," Handbook of Magnetic Materials, vol. 22, pp. 317–379, 2014.

[6] N. Shibata, N. Chino, T. Sato, and H. Chikamasa, "Simultaneous Video Tape Double-Layer Coating Technology," FUJIFILM Res. & Dev. vol. 37, pp.107–111, 1992.

[7] H. Inaba, K. Ejiri, N. Abe, K. Masaki, and H. Araki, "The advantages of the thin magnetic layer of a metal particulate tape," IEEE Trans. Magn. vol. 29, no. 6, pp. 3607–3612, 1993.

[8] H. Inaba, K. Ejiri, K. Masaki, and T. Kitahara, "Development of an advanced metal particulate tape," IEEE Trans. Magn. vol. 34, no. 4, pp. 1666–1668, 1998.

[9] S. Saito, H. Noguchi, Y. Endo, K. Ejiri, T.Mandai, and T.Sugizaki, "Particlulate Magnetic Media with Gbit/in^2-Class Recording Density," FUJIFILM Res. & Dev. vol. 48, pp. 71–75, 2003.

[10] HP white paper, "HP LTO-6 Media Metal Particle and Barium Ferrite," http://www8.hp.com/h20195/v2/GetDocument.aspx?docname=4AA4-4613ENW, Nov 2012.

[11] K. Motohashi, T. Sato, T. Samoto, N. Ikeda, T. Sato, H. Ono, and S. Onodera, "Investigation of Higher Recording Density Using an Improved Co–CoO Metal Evaporated Tape With a GMR Reproducing Head," IEEE Trans. Magn. Vol. 43, pp. 2325–2327, 2007.

[12] P.-O. Jubert, D. Berman, W. Imaino, T. Sato, N. Ikeda, D. Shiga, K. Motohashi, H. Ono, and S. Onodera, "Study of Perpendicular AME Media in a Linear Tape Drive," IEEE Trans Magn. vol. 45, pp. 3601–3603, 2009.

[13] H. Fujiura and S. Nakagawa, "Fabrication of CoCrPt–SiO2 films on flexible tape substrate using facing target sputtering system," J. Magn. Magn. Mat. vol. 310. pp. 2659–2661, 2007.

[14] S. Matsunuma, T. Inoue, T. Doi, T. Matsuu, A. Hashimoto, H. Fujiura, K. Hirata, and S. Nakagawa, "Playback Performance of Facing Targets Sputtered Tape Media on Moving Tape Substrate with a High Speed," IEEE Trans. Magn. vol. 44, no. 11, pp. 3561–3563, 2008.

[15] S. Matsunuma, T. Inoue, T. Doi, T. Matsuu, A. Hashimoto, H. Fujiura, and S. Nakagawa, "Playback performance and microstructure of sputtered tape media formed by facing targets sputtering," J. Magn. Magn. Mat. vol. 320, pp. 2996–2999, 2008.

[16] T. Matsuu, A. Hashimoto, H. Fujiura, S. Matsunuma, T. Inoue, T. Doi, and S. Nakagawa, "Ru-O/Ru hybrid type of underlayer for CoPtCr-SiO2 perpendicular recording media on flexible tape," J. Magn. Magn. Mat. vol. 320, pp. 3000–3003, 2008.

[17] D. Berman, V. H. Chembrolu, T. Topuria, S. Matsunuma, T. Inoue, T. Doi, T. Matsuu, A. Hashimoto, K. Hirata, and S. Nakagawa, "Magnetic Recording Measurements of Sputtered Media on Tape at an Areal Density of 14 Gb/in2," IEEE Trans. Magn. vol. 45, no. 10, pp. 3584–3586, 2009.

[18] Y. Sasaki, N. Usuki, K. Matsuo, and M. Kishimoto, "Development of NanoCAP technology for high-density recording," IEEE Trans. Magn. vol. 41, no. 10, pp. 3241–3243, 2005.

[19] T. Inoue, K. Nakiri, H. Mitsuhashi, M. Fukumoto, T. Doi, Y. Sasaki, and M. Kishimoto, "Playback Performance of Ultrahigh-Capacity Tape Media With Nanosized Composite Advanced Particle (NanoCAP)," IEEE Trans. Magn. vol. 42, no. 3, pp. 465–467, 2006.

[20] T. Nagata, T. Harasawa, M. Oyanagi, N. Abe, and S. Saito, "A Recording Density Study of Advanced Barium-Ferrite Particulate Tape," IEEE Trans. Magn. vol. 42, no. 10, pp. 2312–2314, 2006.

[21] M. L. Watson, R. A. Beard, and S. M. Kientz, "Investigation of Thermal Demagnetization Effects in Data Recorded on Advanced Barium Ferrite Recording Media," IEEE Trans. Magn. vol. 44, no. 11, pp. 3568–3571, 2008.

[22] S. Ölçer, E. Eleftheriou, R. A. Hutchins, H. Noguchi, M. Asai, and H. Takano, "Performance of Advanced Data-Detection Schemes on Barium-Ferrite Particulate Media," IEEE Trans. Magn. vol. 45, no. 10, pp. 3765–3768, 2009.

[23] A. Matsumoto, Y. Murata, A. Musha, S. Matsubaguchi, and O. Shimizu, "High Recording Density Tape Using Fine Barium-Ferrite Particles With Improved Thermal Stability," IEEE Trans. Magn. vol. 46, no. 5, pp. 1208–1211, 2010.

[24] O. Shimizu, T. Harasawa, and M. Oyanagi, "Particle Orientation Effects of Barium Ferrite Particulate Media," IEEE Trans. Magn. vol. 46, no. 6, pp. 1607–1609, 2010.

[25] T. Harasawa, R. Suzuki, O. Shimizu, S. Ölçer, and E. Eleftheriou, "Barium-Ferrite Particulate Media for High-Recording-Density Tape Storage Systems," IEEE Trans. Magn. vol. 46, no. 6, pp. 1894–1897, 2010.

[26] O. Shimizu, T. Harasawa, R. Suzuki, H. Suzuki, N. Yamazaki, A. Musha, Y. Murata, M. Sueki, T. Nishida, and H. Noguchi, "Ba-ferrite Particulate Media for linear Tape System," J. Magn. Soc. Jpn. vol. 35, pp. 27–33, 2011.

[27] O. Shimizu, Y. Murata, Y. Kurihashi, T. Harasawa, M. Asai, M. Sueki, and H. Noguchi, "Long-Term Archival Stability of Barium Ferrite Magnetic Tape," J. Magn. Soc. Jpn. vol. 36, pp. 1–4, 2012.

[28] Y. Kurihashi, O. Shimizu, Y. Murata, M. Asai, and H. Noguchi, "Effect of Thermal Conditions on Bit Error Rate for Barium-Ferrite Particulate Media," IEEE Trans. Magn. vol. 49, no. 7, pp. 3760–3762, 2013.

[29] O. Shimizu, Y. Kurihashi, I. Watanabe, and T. Harasawa, "Distribution of Thermal Stability Factor for Barium Ferrite Particles," IEEE Trans. Magn. vol. 49, no. 7, pp. 3767–3770, 2013.

[30] A. Musha and O. Shimizu, "A Study on Signal Processing for Barium Ferrite Particulate Tape System," IEICE Trans. Electron. vol. E96-C, no. 12, pp. 1474–1477, 2013.

[31] "International Magnetic Tape Storage Roadmap 2012" INSIC http://www.insic.org/news/2012Roadmap/PDF/23%20Roadmap%20-%20Media%204.0.pdf.