

A High-Density Recording Study on Particulate Magnetic Tape using Barium Ferrite Magnetic Particles

Masahito OYANAGI*, Atsushi MOROOKA*, Masahiko MORI*, Yuichi KURIHASHI**, Toshio TADA*, Osamu SHIMIZU*, Hiroyuki SUZUKI*, and Takeshi HARASAWA*

Abstract

We have developed an advanced barium ferrite tape with a magnetic particle volume of 1600 nm^3 ; a surface roughness R_a of 0.9 nm , as determined by optical interferometry; a 10-point average roughness R_z of 27 nm , as determined by atomic force microscopy, and a perpendicular squareness ratio of 0.87 ; the tape features a magnetic particulate coating medium enhanced by fine magnetic particle technology, surface profile design, and particle orientation control. In combination with advanced tape drive technologies, this tape demonstrated an areal density of 123 Gbit/inch^2 , corresponding to a cartridge capacity of 220 TB .

1. Introduction

As ICT, such as cloud computing and Big Data analysis, is increasingly used for studies, businesses and services, it is an urgent issue how to store huge volumes of digital data generated by businesses and governments every day safely at low cost for a long period. Particulate magnetic tape, now in disuse as an audio or video storage medium, is widely used to back up or archive digital data because of these advantages over other data storage products like hard disk drive (HDD): (1) Total cost of ownership (TCO), including introduction and maintenance of the system, is low¹⁾. (2) The tape is stable in long storage and reliable. (3) A road map for a capacity increase to 120 TB per cartridge has been presented²⁾ and it has potential to expand cartridge capacity continuously.

Fig. 1 shows the cartridge capacity trends of a technology demonstration of magnetic tape, an enterprise-class tape cartridge and a linear tape-open (LTO) cartridge. After put on the market in the early 2000s, magnetic tape systems for data storage were expanded in capacity by 40% annually or doubled in about two years. These days, the trend has slowed down especially in LTO systems. That is because metal particles (MP), long used as the storage material of magnetic tape, have reached the limits of particle size reduction. FUJIFILM has studied barium ferrite (BaFe) particles, as an alternative to metal particles, to develop high-density magnetic tape. Working with a tape drive manufacturer, we achieved the technological verification of an areal density of 6.7 Gbit/inch^2 (corresponding to a cartridge capacity of 8 TB) in

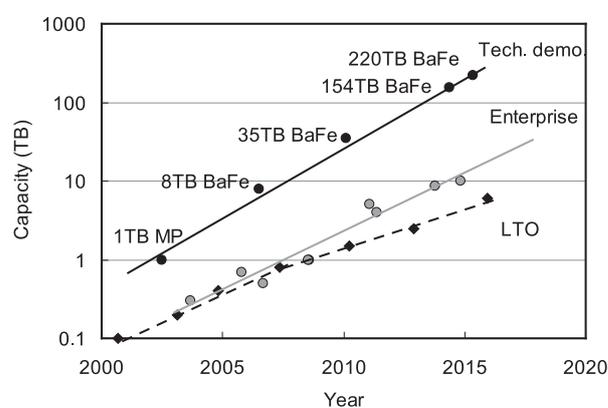


Fig. 1 Capacity trends for technical demonstration of a linear tape system, enterprise-class tape cartridge, and LTO tape cartridge

2006 ³⁾, 29.5 Gbit/inch^2 (35 TB) in 2010 ⁴⁾ and 85.9 Gbit/inch^2 (154 TB) in 2014 ⁵⁾. Based on the verification, tape cartridges with a capacity of up to 10 TB (non-compressed data) have been put on the market, and the slowed down trend towards capacity increase has dramatically grown.

The authors of this paper have continued the study of high-density magnetic tape using barium ferrite particles to further accelerate an increase in capacity of particulate magnetic tape. This paper describes the key technologies of barium ferrite magnetic tape employed for the technology demonstration with an areal density of 123 Gbit/inch^2 ⁶⁾ (corresponding to a cartridge capacity of 220 TB) that was carried out in collaboration with the tape drive manufacturer in April 2015.

Original paper (Received December 1, 2015)

*Recording Media Research Laboratories
Research & Development Management Headquarters
FUJIFILM Corporation
Ogicho, Odawara, Kanagawa
250-0001, Japan

**Recording Media Products Division
FUJIFILM Corporation
Akasaka, Minato-ku, Tokyo
107-0052, Japan

Table 1 Properties of magnetic particle and tape media

Media type	New BaFe tape	BaFe product	Latest MP
<Particle>			
Material	BaFe ¹⁾	BaFe ¹⁾	MP ²⁾
Volume (nm ³)	1600	1950	2830
Coercivity (kA/m)	223	190	189
σ_s (A·m ² /kg)	45	50	103
<Tape media>			
Magnetic properties			
Longitudinal direction			
Coercivity (kA/m)	146	182	217
SQ	0.24	0.39	0.85
Perpendicular direction ³⁾			
Coercivity (kA/m)	263	214	-
SQ	0.87	0.66	-
Surface roughness			
Optical interferometry ⁴⁾			
Ra(nm)	0.9	1.6	2.0
AFM ⁵⁾			
Ra (nm)	1.8	2.0	2.4
Rz (nm)	27	34	40
1) Barium-Ferrite, 2)Metal Particle 3) With demagnetization compensation 4) Measured with HD2000 instrum ents from WYKO; measurement area of 170 μ m \times 236 μ m 5) Measurement area of 40 μ m ²			

2. Characteristics of barium ferrite magnetic tape

Table 1 shows the properties of barium ferrite particles prepared for the technological verification and those of magnetic tape using those particles. The table also shows the properties of barium ferrite product tape and the latest metal product tape for comparison. Barium ferrite particles used for the technological verification have a particle volume of 1600 nm³, coercivity H_c of 223 kA/m and saturation magnetization σ_s of 45 A·m²/kg. This magnetic tape consists of a magnetic layer containing barium ferrite particles, a non-magnetic layer, a substrate film and a back coat layer. The following sections describe the three key technologies for a storage medium to achieve high-density recording: (1) fine magnetic particle technology, (2) surface profile design, and (3) particle orientation control.

2.1 Fine magnetic particle technology

Table 2 shows the characteristics of barium ferrite particles and metal particles.

To achieve high-density recording, the number of particles per unit volume must be increased in the magnetic layer which functions as a data recording layer, to enhance the recording performance such as electromagnetic conversion characteristics. To increase the number of particles, the particle size must be reduced. Metal particles that have been used mainly for magnetic tape are Fe-Co alloy-based metal particles. The

Table 2 Comparison between BaFe particles and metal particles

	Barium ferrite (BaFe)	Metal Particle (MP)
Shape	 Hexagonal platelet shaped	 Acicular
Origin of magnetic energy	Magneto-crystalline anisotropy	Shape anisotropy
Material	BaO(Fe ₂ O ₃) ₆ Oxide	FeCo alloy
Passivation layer	Not Needed	Needed

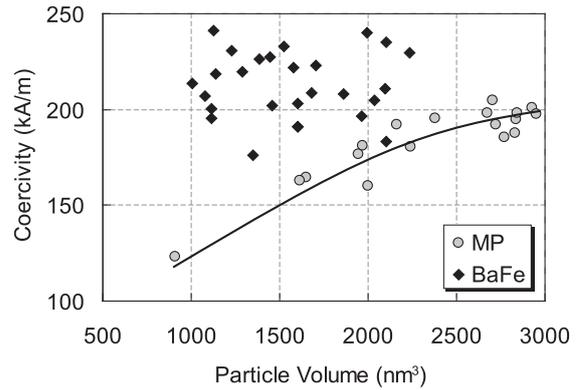


Fig. 2 Particle volume dependence of particle coercivity for BaFe particles and metal particles

origin of magnetic energy is shape anisotropy. When they are reduced in size due to the trend in recent years for high-density recording, it becomes difficult to keep the acicular particle shape. Thus, metal particles have reached the limits of particle size reduction. The origin of magnetic energy of barium ferrite particles, however, is magneto-crystalline anisotropy. The magnetic properties of the barium ferrite particles are not influenced by their shape, and therefore they provide stable magnetization. Unlike metal particles, barium ferrite particles are suitable materials for particle size reduction.

Fig. 2 shows the relationship between particle volume and coercivity of barium ferrite particles and metal particles. The particle volume is an average volume calculated from plate diameters and plate thicknesses observed under a transmission electron microscope (TEM). The coercivity is measured with a vibrating sample magnetometer (VSM). The coercivity of barium ferrite particles can be controlled by varying the aspect ratio, the type or the quantity of substitution element. That is why there are several kinds of particles with different coercivity at the same particle volume. As shown in Table 1, the particle volume of magnetic particles used for barium ferrite product tape is 1950 nm³. However, we have succeeded in reducing the particle volume to around 1000 nm³ while maintaining coercivity sufficient for writing and reading data. By contrast, when the particle volume of metal particles is reduced to 2500 nm³ or below, the coercivity drastically drops. Therefore, it is difficult to achieve high-density

magnetic tape using metal particles.

Fig. 3 shows TEM images of barium ferrite particles used for the latest technological verification and the latest metal particles. The particle volume of the barium ferrite particles is 1600 nm^3 . They have 18% higher coercivity than the latest metal particles while the particle volume is 43% smaller. That shows that barium ferrite particles have sufficient magnetic properties even in fine particles.

As described above, metal particles are Fe-Co alloy-based and thus they need a passivation layer around each particle to prevent oxidative corrosion. Barium ferrite particles, however, are very stable because they are an oxide and free from risk of degradation in quality due to oxidization. This feature is another reason why barium ferrite particles are put to practical use as magnetic tape products although they are finer particles than metal particles.

Fig. 4 shows the degradation in saturation magnetization M_s after the magnetic tape is left for 30 days under severe conditions of 60°C and 90% RH. The tape with metal particles drastically declines in M_s as the particle volume is reduced. This indicates that, as the particle size is reduced, it gets harder to form a uniform passivation layer around the

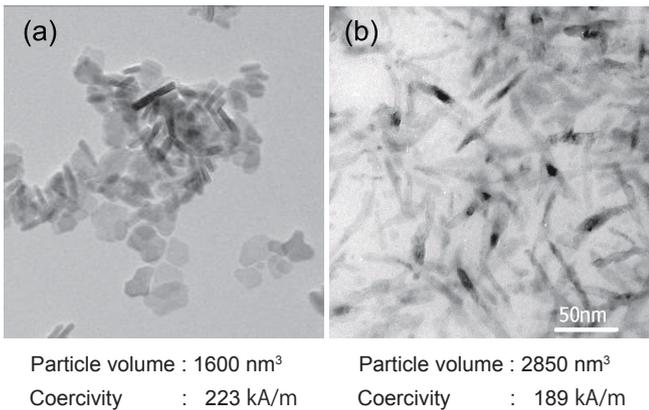


Fig. 3 TEM images of magnetic particles. (a) BaFe particles used for the latest technical demonstration and (b) latest metal particles

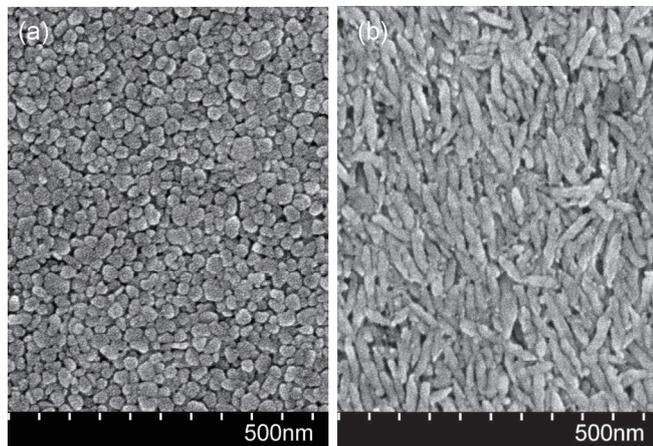


Fig. 5 SEM images of magnetic tape surfaces: (a) BaFe tape for the latest technical demonstration and (b) latest metal particle (MP) tape

particle surfaces, and the quality of metal particles are degraded due to oxidation. By contrast, barium ferrite particles are an oxide, and M_s is hardly degraded regardless of the particle volume. They exhibit stable magnetic properties even under harsh conditions.

Fig. 5 shows the scanning electron microscope (SEM) images of the magnetic layer surfaces of magnetic tapes produced with the barium ferrite particles above and the latest metal particles. Compared with the metal particles, barium ferrite particles are fine, the spaces between the particles are small and the particles are placed on the tape surface densely. This indicates that, compared with metal particles, barium ferrite particles are suitable for high-density recording.

2.2 Surface profile design

To improve the recording performance in addition to the fine magnetic particle technology described above, reducing the distance (spacing) between the magnetic head and the tape is effective. To reduce the spacing, the magnetic tape surface needs to be smoothed as much as possible. It is especially important to design the surface profile of both the substrate film used as a support and the non-magnetic layer applied immediately over the substrate film.

Fig. 6 shows the profile images of magnetic tape surfaces

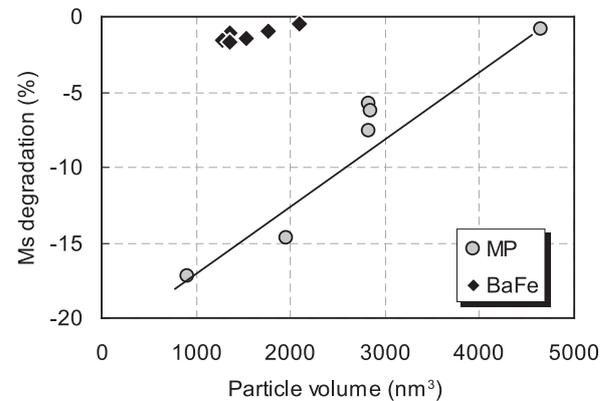


Fig. 4 Comparison of the degradation in saturation magnetization (M_s) between BaFe particles and metal particles in terms of particle volume under conditions of 60°C and 90% RH for 30 days

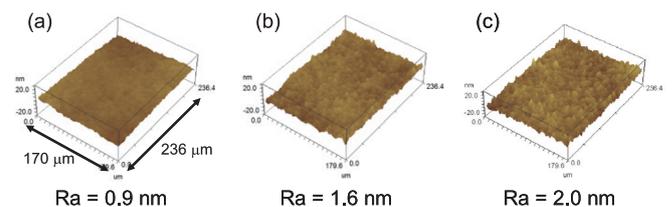


Fig. 6 Surface profile images measured by optical interferometry: (a) new BaFe tape, (b) BaFe product tape, and (c) latest metal particle (MP) tape

measured using WYKO's HD2000 optical interferometry profiler (a measurement area of $170 \mu\text{m} \times 236 \mu\text{m}$). The barium ferrite tape produced for this study has a smoother surface with an arithmetic average roughness R_a of 0.9 nm compared to the one for product tape. That is made possible by removal of long-range waviness with a wavelength of several microns by the control of the non-magnetic layer surface.

Meanwhile, it is generally known that, when the surface of magnetic tape is smoothed, the coefficient of friction against the magnetic head is increased because of an increase in the real contact area between the head and the tape and that the runnability of the tape against the head becomes worse. To solve this problem, it is effective to control the surface profile at a micro-level, for instance by mixing non-magnetic filler particles into the magnetic layer to form small protrusions on the tape surface, in order to reduce the real contact area. In the technological verification, we explored best design of filler particles, such as material and shape, for reducing the real contact area and succeeded in forming many small protrusions on the tape surface and controlling short-wavelength roughness. As a result, we have improved the runnability of smooth tape with little long-wavelength waviness to exceed the level of product tape.

Fig. 7 shows surface profile images of tape obtained by measurement of an area $40 \mu\text{m}$ square with an atomic force microscope (AFM). The barium ferrite tape produced for this study has small protrusions uniformly on the surface while maintaining 10-point average roughness R_z 7 to 13 nm lower than product tape.

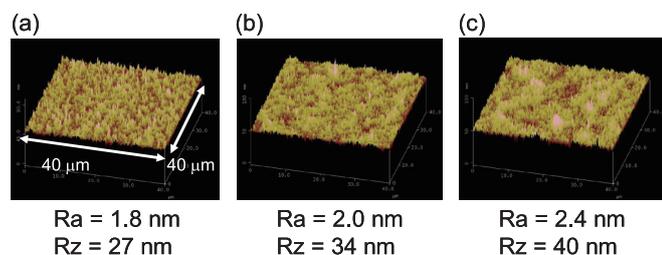


Fig. 7 Surface profile images collected by atomic force microscopy (a) new BaFe tape, (b) BaFe product tape, and (c) latest metal particle (MP) tape

2.3 Particle orientation control

Another important technology to improve the recording performance is orientation control of magnetic particles in the magnetic layer. Metal particles, as they have an acicular shape, are generally oriented in the longitudinal direction of the tape to improve the electromagnetic conversion characteristics. As shown in Table 2, however, barium ferrite particles are in the shape of a hexagonal platelet, and the easy axis of magnetization is perpendicular to the hexagonal surface. So, when applied to the tape, the particles can be oriented

perpendicularly to the tape. About the effect by orientation of barium ferrite tape, a study reports that perpendicular orientation improves the electromagnetic conversion characteristics⁷⁾. In the technological verification, we have oriented the barium ferrite particles perpendicularly when making the tape.

Fig. 8 shows cross-sectional TEM images of magnetic layers of the latest barium ferrite tape, barium ferrite product tape and the latest metal tape with their schematic diagrams. Since barium ferrite product tape currently on the market is not oriented, it can be seen in the image that the magnetic particles are arranged randomly. By contrast, the image of the latest barium ferrite tape produced with the perpendicular orientation technology shows that many of the particles are facing the perpendicular direction.

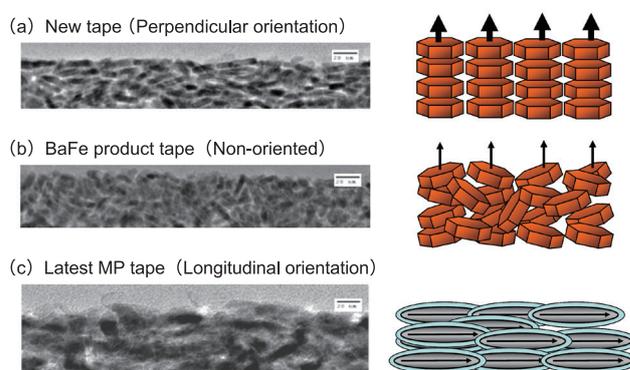


Fig. 8 Cross-sectional transmission electron microscopy images of the magnetic layer: (a) new BaFe tape, (b) BaFe product tape, and (c) latest metal particle (MP) tape

Fig. 9 shows hysteresis loops of M_s measured with VSM. In this measurement, we applied an external magnetic field of 15 kG to the barium ferrite tape in the perpendicular direction and to the metal tape in the longitudinal direction. While the squareness ratio (SQ) of the barium ferrite product tape in the perpendicular direction after correction for the demagnetizing field was 0.66, it was improved to 0.87 with the latest tape. It is as good as the SQ of the latest metal tape in the longitudinal direction.

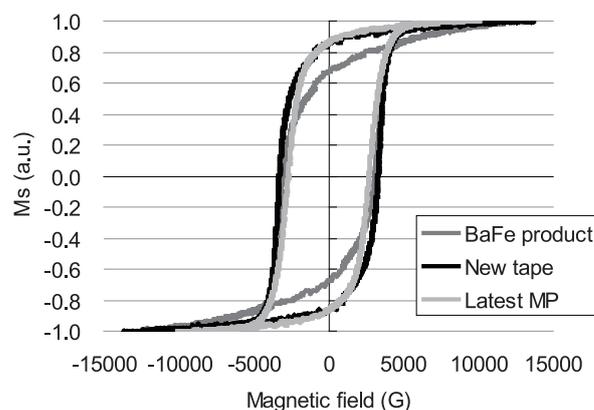


Fig. 9 Magnetic hysteresis loop

3. Conclusion

Using barium ferrite particles with a particle volume of 1600 nm³, we have succeeded in producing magnetic tape with long-wavelength average roughness Ra of 0.9 nm determined by an optical interferometry profiler, short-wavelength 10-point average roughness Rz of 27 nm determined by AFM and perpendicular SQ of 0.87, in the form of a particulate coating medium. In combination with the tape drive manufacturer's technical innovations in tape drive technology, such as the magnetic head and signal processing, this magnetic tape has demonstrated an areal density of 123 Gbit/inch², the highest for particulate magnetic tape⁶⁾, indicating potential for achieving a cartridge capacity of 220 TB.

We have also succeeded in producing magnetic particles with a particle volume of 1000 nm³, which shows potential for still higher-density recording. We believe, therefore, that the capacity of particulate magnetic tape using barium ferrite particles will be further increased.

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