Measurement of Young's Modulus and Stress Analysis of a Magnetic Thin Film*

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In order to evaluate the mechanical properties of a very thin film, this paper proposes a convenient method for separately determining Young's moduli of two thin films of a magnetic recording medium. Furthermore, the particular stress distribution inside a magnetic recording film (two bonded thin films) is analyzed. The internal stress in the medium is not uniform when the medium is subjected to unidirectional tension. The analysis shows that the difference in Poisson's ratio on two thin films causes flexure of the two bonded films under tension, as well as shearing stress at the interface between the magnetic layer and the substrate. Since the shearing stress may cause fatigue damage of the tape edge, detailed FEM analysis on its distribution is carried out.

Key Words: Flexible Magnetic Medium, Young's Modulus, Thin Film, Stress Analysis, Finite-Element Method

1. Introduction

When a flexible magnetic medium is driven, it is in contact with the magnetic recording head. Consequently, its tribological behavior depends on the mechanical properties of the medium. However, it is very difficult to measure the mechanical properties, because the magnetic layer is very thin and is attached to the substrate. There has been an experimental study⁽¹⁾ on Young's modulus of a thick magnetic film which is thicker than the actual magnetic films, but this study did not clarify the relationship between the mechanical properties of thick films and of the actual magnetic layer. Another method⁽²⁾⁻⁽⁴⁾ has been proposed for determining Young's modulus

of a magnetic thin film, the nano-indentation method based on the triangular pyramidal indenter and FEM analysis. This paper proposes a more convenient method for determining Young's modulus of the magnetic layer.

The internal stress in the medium is not uniform when the medium is subjected to unidirectional tension, because it is composed of two different thin films. In particular, the difference in Poisson's ratio in the two bonded thin films under tension causes flexure of the medium, as well as shearing stress at the interface between the magnetic layer and the substrate. Since the shearing stress may cause fatigue damage, detailed FEM analysis on its distribution is carried out.

2. Experimental Method

2.1 Tensile tester

Figure 1 shows the unidirectional tensile tester made by the authors. For simplicity and accuracy, this tester uses a balance and a laser beam. In this tester the sample is suspended vertically, and the load is applied just below the lower side of the sample. Therefore, bending and twisting do not occur, and it is

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Fig. 1 Schematic diagram of the tensile tester

easy to apply an accurate load.

The tester is designed to obtain 10^{-3} -order strain output, the sample length is 100 mm, L (the distance between the laser emission point and the balance) is fixed at 20 m, a (the half-length of the balance) is 0.05 m. x is the difference between the laser emission point and detection point (reflected by the mirror).

The measurement method is as follows. Make the balance horizontally. Fix the lower side of the sample to one side of the balance. Apply the load just below the lower side of the sample, and measure the value x .

Because $L \gg a$, the elongation D of sample is determined as

$$D = ax/2L.$$

Assuming that the magnetic layer is attached to the substrate and deforms according to the deformation of the substrate, Young's modulus of the two bonded layers is determined by formula (1).

$$E_0 \times t_0 = E_M \times t_M + E_S \times t_S \quad (1)$$

Here E represents Young's modulus, t the thickness, the subscript M stands for the magnetic layer, S the substrate and 0 the composite.

In this paper, the method using formula (1) is called the simple method, to distinguish it from the FEM analysis.

2.2 Young's modulus of thick magnetic film and the verification of formula (1)

Table 1 shows the characteristics of the samples. Samples 1 and 3 are composed of only one magnetic layer which is made by a laboratory process only for the experiment and is thicker than the actual film. These magnetic layers are coated to a thickness of about $10 \mu\text{m}$ on a polypropylene film, and then peeled off from the polypropylene film after coating. The polypropylene film is used because it is easy to peel the magnetic layer off of it. Samples 2 and 4 are produced by the same process as above, but are coated on a polyethylene-terephthalate (PET) film and the magnetic layer is not peeled off. The PET film is commonly used as the substrate of magnetic medium.

Formula (1) is verified by comparing Young's modulus of sample 2 with the value estimated by

Table 1 Characteristics of the samples

Sample	Cross-sectional shape		Formulation	
	Thickness (μm)		Width (mm)	Resin (wt. %)
	Magnetic layer	PET		
Sample1	8.1	0	4.0	22
Sample2	7.6	9.4	4.0	22
Sample3	11	0	4.0	30
Sample4	12	9.4	4.0	30
Sample5	2.49	9.81	3.80	17.5
Sample6	2.37	9.70	3.80	22
Sample7	2.60	9.73	3.80	26

formula (1) using Young's moduli of sample 1 and the PET film.

2.3 Young's modulus of the thin magnetic medium

In the case of a magnetic medium for practical use, the thickness is about $2.5 \mu\text{m}$, and it is difficult to peel the layer off from the substrate even if the layer is coated on the polypropylene film. Then, Young's modulus of the thin magnetic layer cannot be measured separately from that of the substrate. It is determined by formula (1) using Young's moduli of only the substrate and two bonded layers.

As shown in Table 1, samples 5, 6 and 7 are produced by an actual production process for practical use, and the magnetic layer is coated to a thickness of about $2.5 \mu\text{m}$ on a different kind of PET film than that for the samples 2 and 4. The formulation of the samples is different only in resin content, and is the same in the contents of magnetic powder, carbon, lubricant and abrasive. Young's modulus of a thin magnetic layer is determined by formula (1) using Young's moduli of two bonded films and the substrate.

The formulation of sample 6 is the same as those of samples 1 and 2. Therefore, the mechanical property of thick magnetic medium is compared with that of thin magnetic medium produced by an actual production process.

3. FEM Analysis

Internal stresses of the two bonded films under unidirectional tension are analyzed by FEM. The MARC program is used for this analysis. Figure 2(a) shows the analytical model. Here, the thickness is in the z -direction, the length is in the x -direction and the width is in the y -direction. In order to be compatible with Saint-Venant's principle and for reasons of

symmetry, the analytical model has thickness d ($= 12.07 \mu\text{m}$ for the sample 6), length $3d$ and width $1.5d$.

Figure 2(b) shows the model and meshings. The model is divided equally into four in the x -direction (see Figure 2(b1)) and the y - z area is divided as shown in Figures 2(b2) and 2(b3). The elements near the edge and the interface are finer than the others to enable detailed analysis of the shearing stress τ_{yz} near the edge and the interface. The number of total elements is 784, and the number of total nodes is 4125.

The boundary conditions are, (1) 0 displacement of nodes on plane $x=0$ in the x -direction, (2) 0 displacement of nodes on plane $y=1.5d$ in the y -direction for reasons of symmetry and (3) displacement of nodes on plane $x=3d$ constrained to 0.5% of $3d$ in the x -direction. It is assumed that the two layers are perfectly bonded to each other. The normal stress σ_n is determined by dividing the reaction force generated on the plane $x=3d$ by the y - z cross section. Young's modulus E_{OFEM} of the two bonded layers is determined by dividing σ_n by the applied strain, and,

Fig. 2(a) FEM analysis model of sample 6
The total thickness is $12.07 \mu\text{m}$, as shown in Table 1

Fig. 2(b) Finite-element mesh (1) Dividing in x direction, (2) In the area ABCD, (3) Detail near the interface, white-box in of (2)

τ_{yz} distribution induced in the section ABCD is investigated.

4. Experimental Results and Considerations

4.1 Thick films made by laboratory process

Table 2 shows the measured values of Young's modulus: 7.0 GPa for sample 1, 11 GPa for sample 3 and 5.3 GPa for the PET film. Table 2 also shows the results of formula (1) using the measured values and the geometry of samples 2 and 4. The result of the simple method roughly agree with the measurements of samples. The small differences may be due to experimental error. Therefore, the simple method may not be completely correct, but it is sufficiently accurate.

4.2 Estimation of Young's modulus of the thin magnetic layer

Young's modulus of the magnetic layer itself is estimated using Young's moduli of the PET film alone and of the composite, using formula (1). Figure 3 shows the relationship between Young's modulus of the magnetic layer alone with its resin content. Young's modulus of only the magnetic layer is higher with higher contents of resin.

In this figure, the results for the thick films are also plotted for comparison of the production process.

Table 2 Young's modulus for thick films obtained by measurement and by the simple method (GPa)

	Measurement	Simple method
Sample 1	7.0	---
Sample 2	5.9	6.1
Sample 3	11	---
Sample 4	7.5	8.5
PET	5.3	---

Fig. 3 Relationship between Young's modulus of magnetic layer alone and its resin content (wt.%)

Young's modulus of the experimental thick films is half that of the thin medium.

The reason for this is that the inside structure of the magnetic layer varies depending on its production process and its composition. The magnetic medium is made by coating magnetic paint on the substrate. The magnetic paint consists of dissolved magnetic powder, carbon, lubricant, resin and abrasive in solvent. After the solvent evaporates from the layer, many pores are formed. The distribution of pores inside the magnetic layer is analyzed by some of the authors, and it is found to correlate with Young's modulus of the magnetic layer⁽⁵⁾.

It is possible to control Young's modulus of a magnetic layer by changing its composition and production process. However, for the same composition, the value obtained for the experimental thick films does not give a correct evaluation of Young's modulus of the thin magnetic layer.

5. Results of FEM Analysis

5.1 Justification of the simple method

Samples 2 and 4 are analyzed by FEM. Young's modulus of the magnetic layer obtained by the above experiment is used in the analysis, and Poisson's ratio is assumed to be 0.3. Young's modulus of the two bonded layers by FEM is defined as E_{OFEM} . Table 3 shows the comparison of Young's modulus values of two bonded layers, obtained by the different method. The estimated values obtained by the simple method and FEM are in good agreement. The measurement values have small differences from the FEM values because of experimental error. The simple method (formula (1)) is justified by FEM analysis.

5.2 Analysis of the thin magnetic layer

5.2.1 Influence of Poisson's ratio Figure 4 shows the relationship between E_M and E_{OFEM} (Young's modulus of bonded film determined by FEM analysis), for E_M values of 10.0, 15.7 and 20.0 GPa. Here, Young's modulus of the PET film E_s is 7.71 GPa and its Poisson's ratio ν_s is assumed to be 0.3. The solid line in Fig. 4 represents E_0 obtained by the simple method. In both cases of $\nu_M = 0.3$ and 0.1, the values are in good agreement with those obtained by the simple method.

Table 3 Comparison of Young's modulus values obtained by different method (GPa)

Sample	Tensile tester	Simple method	FEM
Sample2	5.9	6.1	6.07
Sample4	7.5	8.5	8.52

Here, the magnitude of ν_M is unknown, but because of the deformation of the bonded film, it can be inferred that ν_M is smaller than ν_s . Figures 5(a) and (b) show the deformation of two bonded layers under unidirectional tension, obtained by FEM analysis at section ABCD of the model. Usually, when the magnetic medium for practical use is subjected to unidirectional tension, the magnetic layer becomes convex. But, in the case of $\nu_M = 0.3$, this deformation does not occur, as seen in Fig. 5(a). In the case of $\nu_M = 0.1$, the magnetic layer becomes convex, as seen in Fig. 5(b). Strictly speaking, quantitative discussion is necessary, but it is obvious from this deformation that ν_M is smaller than ν_s .

In Fig. 5(a) and 5(b), the displacements are exaggerated 500 times.

5.2.2 Distribution of internal stress The stress distribution at the section ABCD shows the existence of a maximum τ_{yz} near the edge of the interface. Figure 6 shows the distribution of τ_{yz} in the case of $E_s = 7.71$ GPa, $\nu_s = 0.3$, $E_M = 15.7$ and $\nu_M = 0.1$. In the case of the thick of magnetic layer being 2.37

Fig. 4 Estimation of Young's modulus of the two bonded layers by FEM analysis, and comparison with that of the simple method

Fig. 5 Deformation of cross section ABCD for sample 6. $E_M = 15.7$, $E_s = 7.71$ GPa

Solidline : before loading

Brokenline : after loading

(Displacements are exaggerated 500 times.)

In the case of $\nu_M \neq \nu_s$, the magnetic layer become convex

Fig. 6 Distribution of τ_{yz} at the crosssection ABCD

μm thick and the substrate $9.70\text{ }\mu\text{m}$ thick, the peak of τ_{yz} is $0.1\text{ }\mu\text{m}$ from the edge, and its magnitude is about 7.2% of the normal stress σ_n . τ_{yz} decays with distance from the edge, but this maximum shearing stress must be distinguished from the singular stress distribution at the interface between some materials.

Figures 7(a)–(f) show the distribution of τ_{yz} at section ABCD. In the case of $\nu_M = 0.3$, there is no τ_{yz} , but when ν_M does not equal ν_S , τ_{yz} exists. The magnitude of τ_{yz} differs slightly depending on E_M . Thus, τ_{yz} is caused by the difference in Poisson's ratios between layers.

The two bonded layers subjected to tension with different Poisson's ratio exhibit maximum shearing stress at the edge of the interface between the two layers. The magnitude of τ_{yz} is about 7% of normal stress when Poisson's ratios of the two layers are 0.1 and 0.3.

When the magnetic tape is driven, the tape is bent by the many guide pins. These bends apply the tension and compression to the magnetic layer, and shearing stress occurs at the edge of the tape. This shearing stress causes fatigue of the magnetic medium, and the edge of the magnetic tape is sometimes damaged. Edge damage may be caused mainly friction by the guide pins, but the above shearing stress may contribute to fatigue and fracture of the tape edge.

6. Conclusions

In this paper, a convenient method for determining Young's modulus of a thin film was proposed. Young's modulus of the magnetic layer of magnetic media was measured, and the two bonded layers subjected to tension were analyzed by FEM, and the internal stress distribution are clarified.

6.1 Measurement of Young's modulus

In order to evaluate Young's modulus of a thin magnetic layer, the unidirectional tensile tester and a simple method were proposed.

Fig. 7 Distribution of τ_{yz} at the interface
(a)–(c) $\nu_M = 0.3$, (d)–(f) $\nu_M = 0.1$
($E_S = 7.71\text{ GPa}$, $\nu_S = 0.3$)

(1) By experiment and FEM analysis, it was verified that the simple method is a satisfactory method.

(2) Young's modulus of only the magnetic layer with varying resin content was estimated by the simple method. Young's modulus of the magnetic layer is higher with higher resin content.

(3) Young's modulus of the thick film made by the laboratory process is half that of an actual magnetic layer, and does not give a correct evaluation of Young's modulus of the thin magnetic layer.

6.2 FEM analysis

The two bonded layers subjected to unidirectional tension were analyzed and internal shearing stress was investigated.

(1) Because of the convex deformation of commercial magnetic tapes under unidirectional tension, it was estimated that $\nu_M < \nu_S$.

(2) In the case of $\nu_M = 0.1$ and $\nu_S = 0.3$, the τ_{yz} peak appears near the edge of the interface between two bonded layers.

(3) These results are applicable to two bonded layers in general. The two bonded layers may become fatigued or fractured near the edge of the interface due to shearing stress. In order to design good two bonded layers, the appropriate combination of Young's modulus and Poisson's ratio must be considered.

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