# SURFACE MORPHOLOGY AND MICROTRIBOLOGICAL BEHAVIOR OF MAGNETIC AUDIO TAPES①

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**ABSTRACT** With the rapid development of magnetic storage media in home and industry, it's very urgent to investigate the tribological behavior of recording media and improve their tribological properties. In the late 1980's, the invention of the friction force microscope makes it feasible to evaluate the surface morphology and microtribological properties at nano scale. The surface morphology, surface adhesion and microtribological behavior of magnetic audio tapes were investigated by a new developed atomic force/friction force microscope (AFM/FFM). The results show that the surface roughness and grain size of three kinds of audio tapes made in China are almost equal to those of abroad tapes. The friction force at a given load and friction coefficient of *Sony* tape are larger than those of *Nature* tapes. There is a good correspondence between the friction force image and the slope of surface topography. The friction force increases with the load, the slope of surface topography and the surface adhesion.

**Key words** audio tapes surface morphology microtribological behavior AFM/FFM

## 1 INTRODUCTION

Magnetic storage media such as audio tapes, video tapes and floppy disks have wide applications in home and industry because of their low price, high recording density and easy carrying characteristics. Bhushan[1] pointed out that the magnetic storage industry is expected to grow by a factor of five or more in the next decade, and the magnetic recording density will be improved by at least one order of magnitude. This growth will need to be accompanied by dramatic improvement in tribological properties of magnetic head and medium system. The need for the higher and higher recording density requires that the flying height between head and medium should be as low as possible, now the flying height is on the order of 0.1 micrometer which compared to the surface roughness of the mating members. This structural characteristic will cause friction and wear of magnetic head and media, and then results in data reliability problems. On the other hand, the magnetic head and media system will experience different physical contacts under nano Newton's vertical contact force during start, stop and running at high speeds, and the grain size of magnetic particles is also in nano scale. So the magnetic system's friction and wear become the main research area of microtribology with practical industry applications[2].

Since the atomic force microscope and friction force microscope were developed in 1980's[3,4], several researchers have investigated the microscopic friction force on magnetic media by friction force microscope[5], but there is less microtribological investigation on audio tapes. In 1995, we cooperated with the Institute of Chemistry, Chinese Academy of Science, and developed a new scanning probe microscope CSPM-930a which combined the function of STM, AFM and FFM[6]. This apparatus can

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measure the normal load, friction force, observe and analyse the surface morphology with nano meter's and nano Newton's resolution. All these make it feasible to evaluate the surface morphology and microtribological properties at nano scale[7], and then to develop the new recording media with higher and higher density.

In this paper, the surface morphology and microtribological characteristic of five magnetic audio tapes were carried out by this new scanning probe microscope. On the basis of experimental results, the relationship between lateral force and friction force, and the correspondence among the friction force, surface topography and the slope of surface topography were discussed.

## 2 EXPERIMENTAL PROCEDURES

Magnetic audio tapes named *Sony*, *TDK* (abroad tape), *ZZZ*, *Top*, *Nature* (home made tapes) were chosen as test samples. The surface morphology and microtribological behavior were carried out in CSPM-930a scanning probe microscope. The normal spring constant of $Si_3N_4$ cantilever used in the test is 0.38 N/m.

### 2.1 Surface morphology

The surface morphology of five magnetic audio tapes was observed by height constant mode along the $X$ direction. The reference current $I_{ref}$ is -0.20 nA, the scanning speed is $2\times10^{-6}$ m/s. The surface roughness parameters such as $R_a$, $R_q$, $S_m$, $S$, $\lambda_a$, $\lambda_q$ were calculated by the analysis methods of three dimensional surface topography[8].

### 2.2 Fractal dimension

Fractal dimension can be calculated by many different methods. In order to compare these methods, the power spectrum (PSD), slit island, length of surface profile and sandbox methods were used. After observation of surface topography, the fractal dimension of audio tapes was calculated by the analysis program of digital image[8].

### 2.3 Micro friction test

The reference current $I_{ref}$ related to the load in the friction test was first determined by $I_{ref}$—$V_z$ curves, and then the tip scanned back and forth on the sample surface in the $Y$ direction at a given load (normal force). The normal force and friction signals were respectively recorded by upper and lower halves, left and right halves of the quadrant photo diode. The friction force image is the half of the difference between the average $Y$ (scanning in positive $Y$ direction) and $-Y$ (scanning in negative $Y$ direction) friction signals. the friction force signal value ($f$) is equal to the average of friction force image $f(I, J)$[7].

### 2.4 Adhesion force

The force versus tip-substrate surface separation curve was measured during the tip approaching and withdrawing process. The adhesion force $f_{ad}$ can be determined by multiplying the cantilever spring constant $k$ by the distance at which the cantilever was deflected just before the occurrence of surface separation.

## 3 RESULTS

### 3.1 Surface morphology

Fig.1 shows the surface morphology of five audio tapes. It is observed that *ZZZ* and *Nature* tapes are mainly composed of rod-like magnetic particles, and the particles of *Top* tape are in rod and block states. The abroad *Sony* and *TDK* tapes are mainly in block state, only a few rod-like particles are found in *Sony* and *TDK* tapes. In general, there is only a slight difference among these audio tapes.

### 3.2 Surface roughness

The surface roughness parameters of five magnetic audio tapes calculated by data analysis program are shown in Table 1. The surface roughness and grain size of three home made tapes are almost equal to those of abroad *Sony* and *TDK* tapes. It is found that there is no clear difference between home made and abroad tapes. The calculating results coincide with the observation of surface topography of audio tapes.

### 3.3 Fractal dimension

Fig.2 shows the curves for calculating fractal dimension by power spectrum method and sandbox method. It can be seen that there is a linear relationship between power spectrum $S(f)$ and frequency $f$ in the power spectrum method, and the numbers $N(a)$ of counting box and the yardstick $a$ in the sandbox method. After linear regression, the following formula can be obtained:

$$\lg S(f) = -2.48\lg f + 6.7998 \quad (1)$$

(Power spectrum method, $Y$ direction)

$$\lg S(f) = -2.14\lg f + 6.5982 \quad (2)$$

(Power spectrum method, $X$ direction)

$$\lg N(a) = -2.35\lg a + 5.6971 \quad (3)$$

(Sandbox method)

According to the slope of the above formula, the fractal dimension is then calculated by the fractal theory. The fractal dimension of five audio tapes corresponding to sandbox, power spectrum, length of surface profile and slit island methods is tabulated in Table 2. It can be found that there is a slight difference among three methods in the value of fractal dimension except the length of surface profile method. The fractal dimension of three home made tapes are almost equal to that of abroad tapes. Combined with the surface roughness parameters in Table 1, the conclusion can be made that the surface characteristics of home made audio tapes are almost the

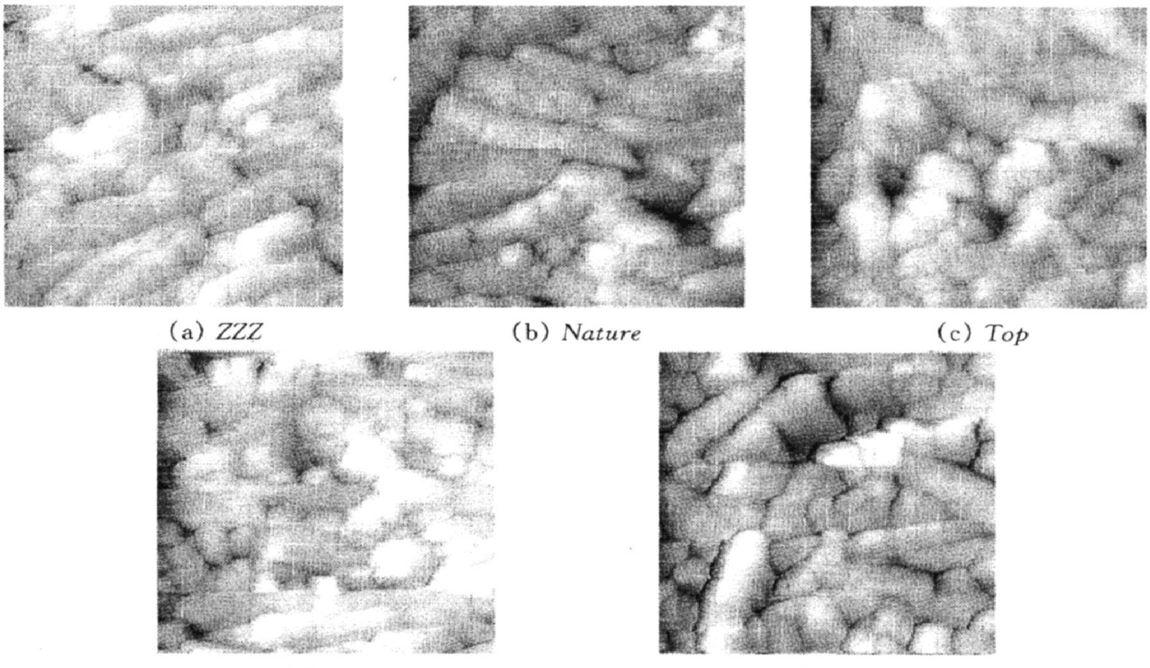



**Fig.1** Surface topographies of five magnetic audio tapes

**Table 1** Surface roughnesses of five magnetic audio tapes (nm)

| Samples | $R_a$ | $R_q$ | $S_m$ | $S$ | $\lambda_{ax}$ | $\lambda_{qx}$ | $\lambda_{ay}$ | $\lambda_{qy}$ |
|---|---|---|---|---|---|---|---|---|
| *ZZZ* | 3.5 | 4.4 | 329 | 99 | 863 | 1 328 | 1 234 | 1 694 |
| *Nature* | 4.6 | 5.9 | 286 | 93 | 1 034 | 1 538 | 1 507 | 2 021 |
| *Top* | 2.7 | 3.5 | 329 | 112 | 983 | 1 493 | 1 303 | 1 830 |
| *Sony* | 2.7 | 3.6 | 294 | 94 | 932 | 1 586 | 1 396 | 1 917 |
| *TDK* | 4.5 | 5.8 | 387 | 126 | 793 | 1 211 | 1 183 | 1 661 |

same as those of abroad tapes.

### 3.4 Characteristics of micro friction

Fig.3 shows the correspondence among surface topography, slope of surface topography and friction force image of *Nature* audio tape. By comparing these three images, it can be seen that there is similarity among these three images, and the great changes of brightness in the edge of particles are occurred.

The dependence curves of friction force signal of *Sony* and *Nature* audio tapes on the nano scale load is shown in Fig.4. The friction force signal of audio tapes is almost increased linearly

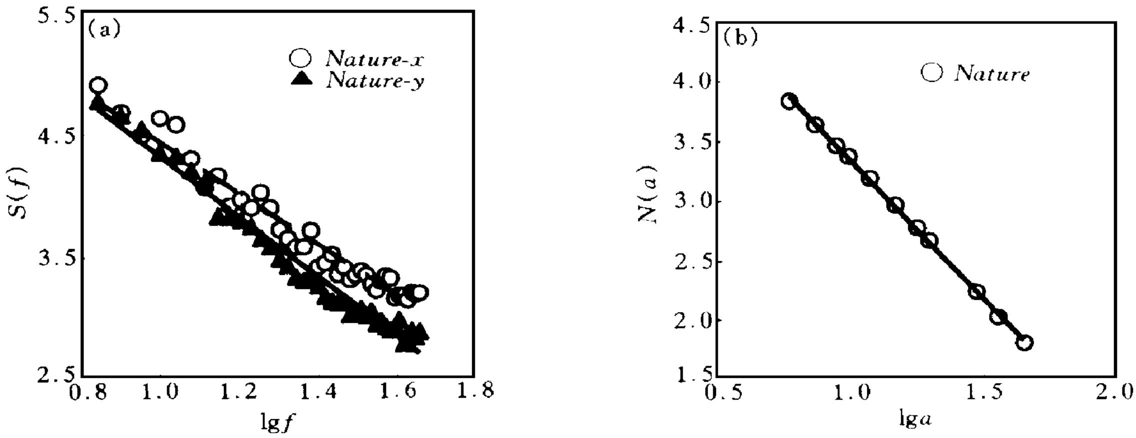
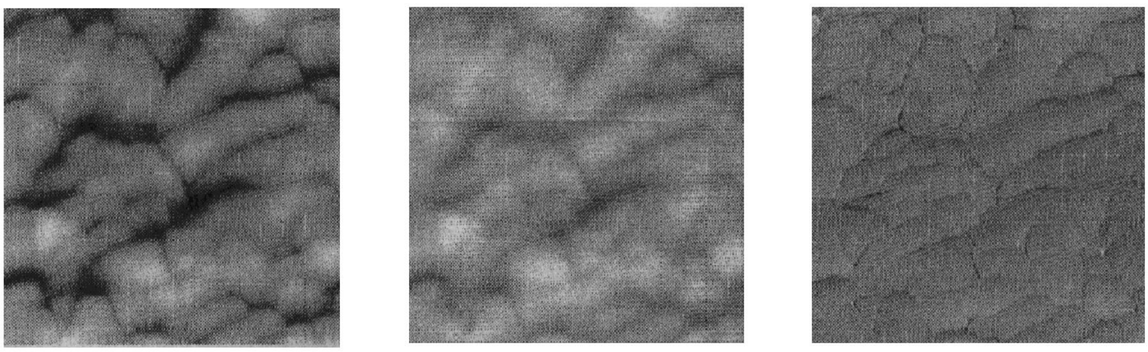



**Fig.2** Curves for calculating fractal dimension by (a) power spectrum method and (b) sandbox methods

**Table 2** Fractal dimension by different methods

| Samples | Length of profile | | PSD | | Slit island | Sandbox |
|---|---|---|---|---|---|---|
| | X | Y | X | Y | | |
| *ZZZ* | 1.001 | 1.002 | 1.41 | .34 | 2.29 | 2.23 |
| *Nature* | 1.010 | 1.015 | 1.43 | 1.26 | 2.29 | 2.35 |
| *Top* | 1.001 | 1.002 | 1.42 | 1.28 | 2.28 | 2.33 |
| *Sony* | 1.001 | 1.001 | 1.35 | 1.33 | 2.26 | 2.36 |
| *TDK* | 1.002 | 1.003 | 1.28 | 1.23 | 2.24 | 2.32 |



(a) Surface topography (b) Slope of surface topography (c) Friction force image

**Fig.3** Correspondence among surface topography, slope of surface topography and friction force image of *Nature* tape with the load. After linear regression, the following formulae can be obtained:

$$f = 0.092\,p + 20.13\ (Sony\ \text{tape}) \qquad (4)$$

$$f = 0.077\,p + 1.83\ (Nature\ \text{tape}) \qquad (5)$$

According to the principle of FFM, the friction force can be calculated by multiplying the torsion stiffness of the cantilever by the distance that the cantilever is turned around in the friction test along $Y$ or $-Y$ direction, i.e. the friction force signal. The torsion stiffness is related to the geometry of the cantilever and the mechanical properties of $Si_3N_4$. Because there is slight difference between different cantilevers, the precise value of the friction force is very difficult to calibrate. According to these factors, the friction force image signal can be used as the representative of the real friction force if only the difference between different magnetic media is required to compare, and the slope of friction force signal vs load is referred to as the friction coefficient under the micro friction test[7]. From Fig.4, it is found that the friction force of *Sony* tape is larger than that of *Nature* tapes at the same load, and the friction coefficient of *Sony* tape is also larger than that of *Nature* tape.

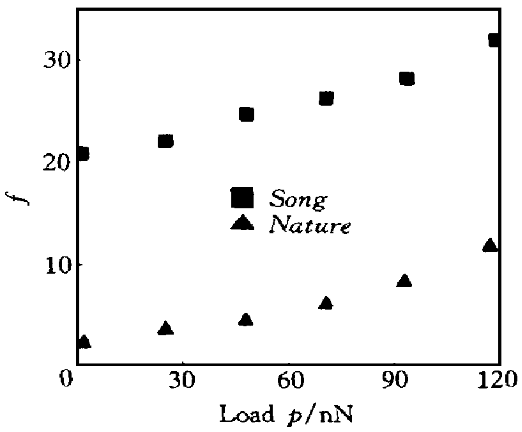



**Fig.4** Dependence of friction force signal of *Sony* and *Nature* tapes on load

## 4 DISCUSSION

### 4.1 Relationship between lateral force and friction force

According to the principle of FFM, the friction force signal is the difference between the right and left halves of detected diode when the tip scans along the $Y$ and $-Y$ direction. But because of the experimental errors, the difference between the right and left halves of diode is the lateral force signal which contains the friction force signal and other lateral signals. In order to separate the friction force from the lateral force, the method of scanning simultaneously along $Y$ and $-Y$ direction is chosen, namely

In $Y$ direction:

$$F_Y(I, J) = f_0(I, J) + f(I, J) \qquad (6)$$

In $-Y$ direction:

$$F_{-Y}(I, J) = f_0(I, J) - f(I, J) \qquad (7)$$

$$f(I, J) = (F_Y(I, J) - F_{-Y}(I, J))/2 \qquad (8)$$

where $F_Y(I, J)$ and $F_{-Y}(I, J)$ are separately the lateral force signal in the $Y$ and $-Y$ direction, $f(I, J)$ is the friction force signal which will be opposite when the tip scans along the opposite direction, and $f_0(I, J)$ is the lateral force besides the friction force. The value of friction force signal at a given load can be calculated by

$$f = \frac{1}{180 \times 180} \sum_{I, J=1}^{180} f(I, J) \qquad (9)$$

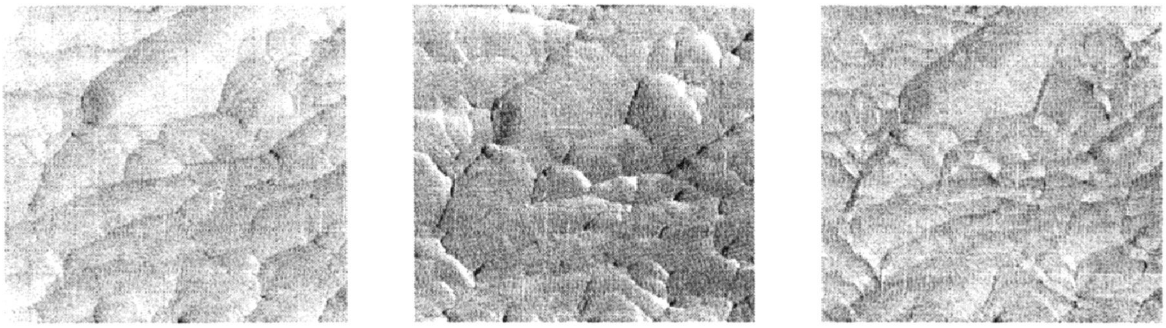
Fig.5 shows the lateral force image along $Y$ and $-Y$ direction and the friction force image. From Fig.5, it can be seen that there is not only similarity but also difference among these three images. It is by this difference that the friction force signal is distinguished from the lateral force signal.

### 4.2 Relationship among surface profile, slope of surface profile and friction force profile

As for the relationship among surface profile, slope of surface profile and friction force profile, there are two viewpoints, one is Mate's theory[9]: the variation in friction force comes from the variation in the attractive force between the tip and the tape surface, and the major component of the attractive adhesive force is the van der Waals force:

$$F_{vdw} = 4\pi R(\gamma_1 \gamma_d)^{1/2}(D_0^2/D^2) \qquad (10)$$

where $D_0 \sim 0.2$ nm and $D$ is the separation distance of the means of the tip and the tape surface. As a consequence of the strong $D^{-2}$ depen-



(a) Y direction (b) − Y direction (c) Real friction force

**Fig.5** Lateral force images along Y and − Y direction and friction force image

dence, the tip should experience a much weak van der Waals force on the top of a topography summit, and a much strong force in a valley. As the tip scans from a high to low point, the adhesive force between the tip and the sample increases with a corresponding increase in the friction force. The other is Bhushan's ratchet theory[10]: there is a strong correlation between the friction force and the slope of surface profile. In the ascending process, $\mu \sim \mu_0 + \text{tg}\,\theta$, in the descending process, $\mu \sim \mu_0 - \text{tg}\,\theta$, where $\mu$ is the local friction coefficient, $\mu_0$ is the friction coefficient in the horizontal plane, and $\theta$ is the angle of the asperity with the horizontal plane.

To examine the relationship among the surface topography, slope of surface roughness and friction force image, the surface profile, the slope of surface profile calculated along the sliding direction and the corresponding friction force profile are taken and shown in Fig.6. By comparing these three profiles, the resemblance between the friction force profile and the slope of surface roughness is stronger than that between the friction force profile and the surface profile.

To further verify the relationship among surface topography, slope of surface profile and friction force, the variation of friction force signal $F(I,J)$ at 100 nN load with the surface topography $Z(I,J)$ and slope signal of surface profile $S(I,J)$ are shown in Fig.7. It is observed from Fig.7 that there is an obvious linear relationship between the friction force signal and the slope of surface profile. As for the relationship

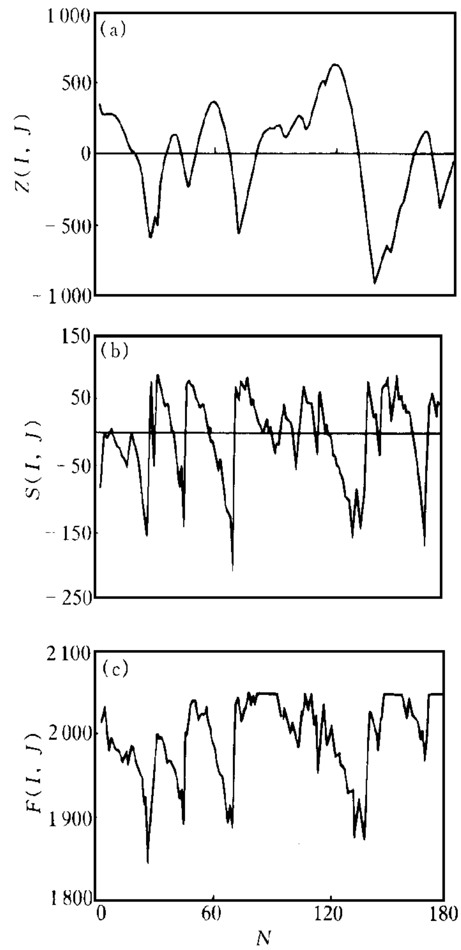



**Fig.6** (a) Surface profile $Z(I,J)$, (b) Slope of surface profile $S(I,J)$, and (c) Friction force profile $F(I,J)$

between $F(I, J)$ and $Z(I, J)$, there is a correspondence to some extent, but this correspondence is not clear and the data are very discrete. All these show that the friction force correlates to the slope of surface profile. From the correlation functions among the surface profile, the slope of surface profile and the friction force profile[7], it's also proved that the friction force profile does correspond to the slope of surface profile.

### 4.3 Adhesion force

In order to explain the difference among *Sony* and *Nature* tapes, the force vs tip-sample distance curves of *Sony* and *Nature* tapes were measured (Fig.8). Through calculating, the adhesion force is determined to be 14.8 nN for *Sony* tape, 6.8 nN for *Nature* tape, i.e. the adhesion force of *Sony* tape is larger than that of *Nature* tape.

The friction force $f$ can be given as follows[11]:

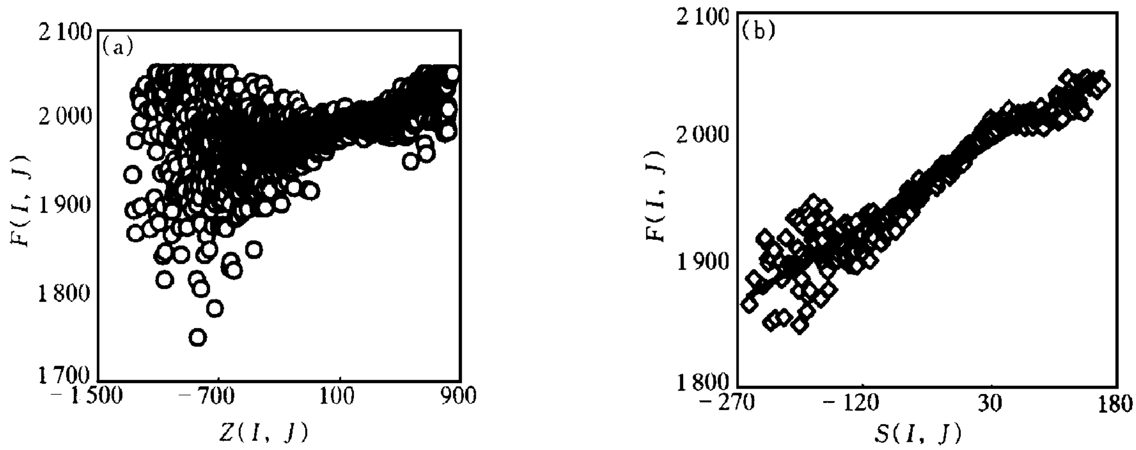



**Fig.7** Variation of friction force signal $F(I, J)$ with surface topography $Z(I, J)$ and slope of surface profile $S(I, J)$

(a) — $F(I, J)$ vs $Z(I, J)$; (b) — $F(I, J)$ vs $S(I, J)$

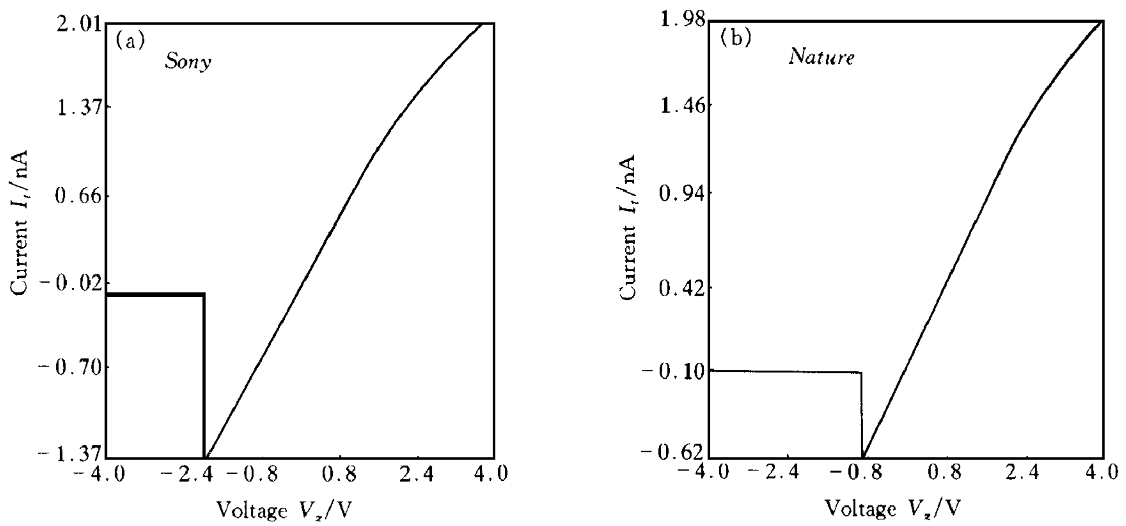



**Fig.8** Tip-sample distance curves of *Sony* and *Nature* audio tapes

(a) — *Sony*; (b) — *Nature*

$$f = \mu(L_{ap} + F_{ad}) \quad (11)$$

Here $\mu$ is the friction coefficient, $L_{ap}$ is the applied force, and $F_{ad}$ is the adhesion force. From the micro friction coefficient and the adhesion force, the difference of the micro friction characteristic between *Sony* and *Nature* tapes can be explained. The friction force is proportional to the adhesion force.

## 5 CONCLUSIONS

(1) The surface roughness and grain size of three home made magnetic audio tapes are almost equal to that of abroad *Sony* and *TDK* magnetic audio tapes.

(2) The micro friction force of *Sony* audio tape is larger than that of *Nature* audio tape at the same load, and the friction coefficient and adhesive force of *Sony* audio tape are also greater than that of *Nature* tape.

(3) There is a good correspondence between friction force and the slope of surface topography. The friction force increases with the load, slope of surface topography and the surface adhesion force.

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