# First-order reversal curves of magnetic recording tapes*

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(Received 31 January 2009; revised manuscript received 21 December 2009)

The interaction and its variation between magnetic grains in two kinds of magnetic recording tapes are investigated by first-order reversal curves (FORC) and the $\delta M$ method. The composition and microstructure of the samples are characterised by x-ray diffraction and scanning electron microscope. The FORC diagram can provide more accurate information of the interaction and its variation, but the $\delta M$ curves cannot. The positive interaction field and the large variation of the interaction field have opposite effects on the $\delta M$ curve.

**Keywords:** magnetic interaction，first-order reversal curves, the $\delta M$ method, magnetic recording tape

**PACC:** 7550S, 7560

## 1. Introduction

Although high-density magnetic recording research focused on hard disc magnetic recording,[1−5] the magnetic recording tapes are still widely used now (for example, mini DV tapes, cards, bank books etc.). Most of the world's data are primarily stored and archived on magnetic recording tapes because of its long shelf life and favourable cost factors.[6] It is not easy to investigate the interaction field between the magnetic grains in magnetic recording tapes by the conventional $\delta M$ method because the $\delta M$ curve depends on not only the interaction field but also the variation of interaction field.[7,8] The $\delta M$ method is invalid for investigating the interaction when the effect of the interaction field on the $\delta M$ curve is smaller than the effect of the variation of interaction field on the $\delta M$ curve. The interaction field between the magnetic grains in magnetic recording tapes is generally small. Therefore, the $\delta M$ method might be invalid for investigating the interaction field in magnetic recording tapes. First-order reversal curves (FORC) diagram is a new tool that is used to analyse magnetic properties of ferromagnetic materials.[9] It is believed that the FORC diagrams can lead to more detail understanding of interactions than the $\delta M$ method.[9] The FORC diagrams of the magnetic materials including magnetic floppy disc,[9] longitudinal and perpendicular magnetic recording media,[10,11] magnetic nanodots,[12,13] magnetic nanowire,[14] spin glasses,[15] exchange spring permanent magnets,[16−18] and antiferromagnetic exchange coupled Co/Pt multilayer film[19] have been measured. The detail FORCs measurement has been described in Ref. [9]. In this paper, the interaction field between the magnetic grains in two kinds of magnetic recording tapes is investigated using the $\delta M$ method and FORC method with the assistance of x-ray diffraction (XRD) and scanning electron microscope (SEM) analysis.

## 2. Experiment

Two kinds of magnetic recording tapes denoted by A and B were fabricated by different companies. The compositions and microstructures of samples A and B were investigated by XRD and SEM. Magnetic hysteresis loops, $\delta M$ and FORC curves were measured with an alternate gradient force magnetometer (AGFM).

The FORC distribution is defined as a mixed second-order derivative[9]

$$\rho(H_{\rm r}, H_{\rm a}) = -\partial^2 M(H_{\rm r}, H_{\rm a})/2(\partial H_{\rm r}\partial H_{\rm a}). \qquad (1)$$

The FORC distribution $\rho$ is plotted against ($H_{\rm r}$, $H_{\rm a}$) coordinates on a contour map. Alternatively the FORC distribution can be plotted in coordinates of ($H_{\rm c}$, $H_{\rm b}$), where $H_{\rm c}$ is the local coercive field and $H_{\rm b}$ is the local interaction or bias field. This transformation is accomplished by a simple rotation of the coordinate system defined by: $H_{\rm b} = (H_{\rm a} + H_{\rm r})/2$ and

*Project supported by the National Natural Science Foundation of China (Grant Nos. 50672008 and 50971023) and Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20090006120019).

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$H_c = (H_a - H_r)/2$. The coordinates of ($H_c$, $H_b$) are used in this paper.

## 3. Results and discussion

The XRD patterns of samples A and B are shown in Fig. 1. One can see that only $\gamma$-$Fe_2O_3$ phase is found for both samples. Relative intensity of XRD peaks of these two samples is close to those of the powder diffraction pattern. Therefore, there is no preferred orientation for these two samples.

Figure 2 shows the hysteresis loops of samples A and B. The measurements were done along both the longitudinal and the long transverse directions. The squareness and coercivity in the longitudinal direction are higher than in the long transverse direction for both samples A and B. From Fig. 3, one can clearly see that the texture of the magnetic recording tapes is along the longitudinal direction. The anisotropy of the hysteresis loops should be due to the texture of the magnetic recording tapes. The dot defects shown in Fig. 3(b) might be one of the reasons for the lower $H_c$ of sample B. The defects can enhance the demagnetizing field that might reduce the coercivity of the magnetic recording tape.

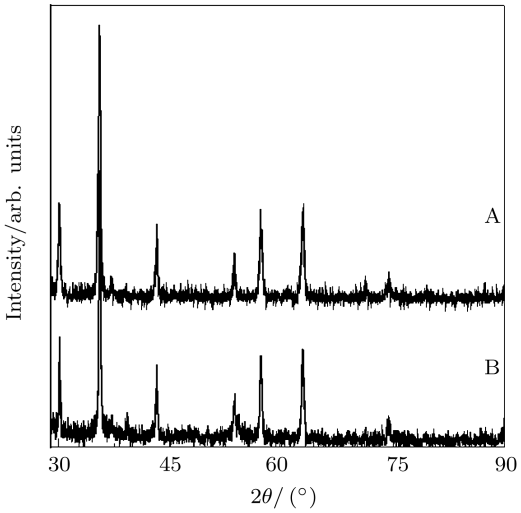



**Fig. 1.** XRD patterns of samples A and B.

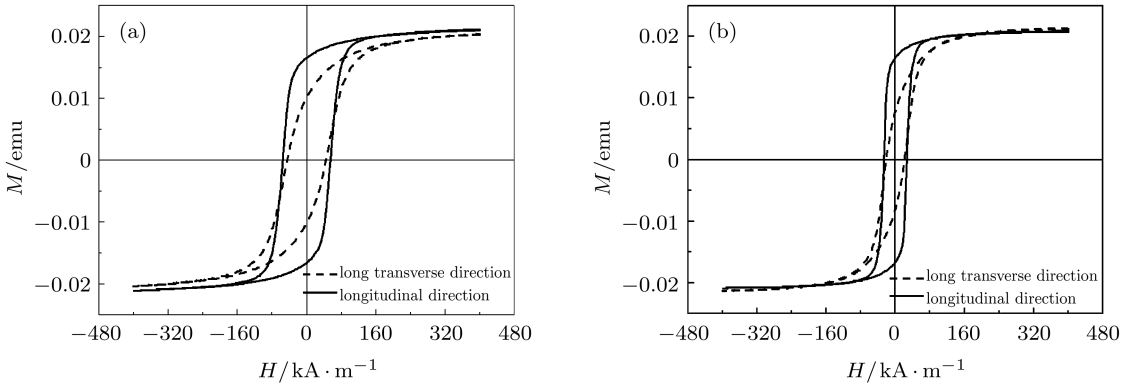



**Fig. 2.** Hysteresis loops of samples A (a) and B (b).

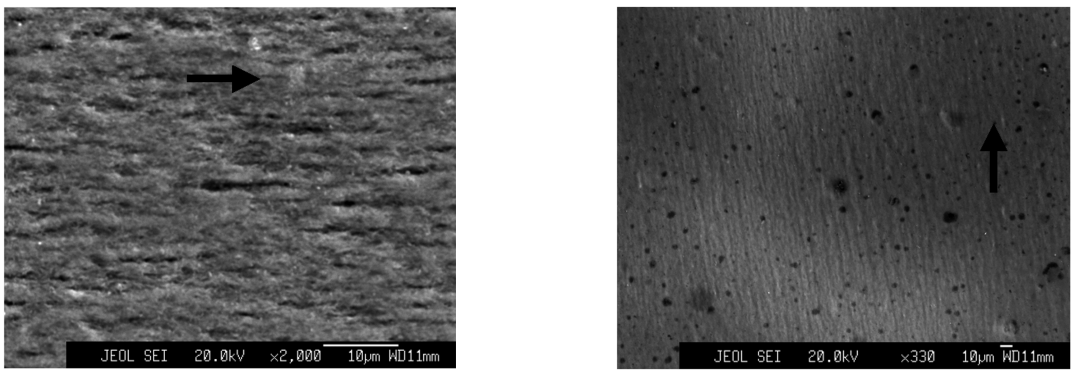



**Fig. 3.** SEM images for samples A (a) and B (b). The arrows show the longitudinal direction of the magnetic recording tapes.

In order to investigate the interaction between magnetic grains, $\delta M$ curves were measured along the longitudinal direction for both samples A and B. The $\delta M$ curves normalised by saturated remanence are shown in Fig. 4. From Fig. 4, only the negative $\delta M$ peaks are observed for samples A and B. The demagnetising field can lead to a negative $\delta M$ peak. Besides the demagnetising field, a large enough variation of interaction field can also lead to a negative $\delta M$ peak even the interaction is positive, which can lead to a positive $\delta M$ peak.[7,8]

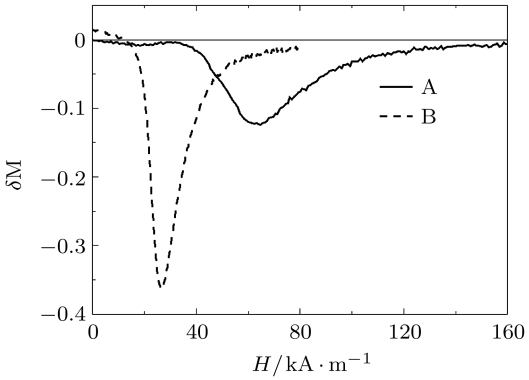



**Fig. 4.** $\delta M$ curves for samples A and B.

FORC diagrams can provide more detailed information of interaction field and the variation of interaction field than the $\delta M$ method.[9] In order to clarify the interaction field property and the variance of interaction field in samples A and B, the FORCs of samples A and B have been measured along the longitudinal direction. Based on Eq. (1), the samples' FORCs shown in Figs. 5(a) and 6(a) were transformed into the FORC diagrams shown in Figs. 5(b) and 6(b), respectively. In Figs. 5(b) and 6(b), the $x$ and $y$ coordinates are $H_{\rm c}$ and $H_{\rm b}$, respectively. The unit of the coordinates is kA/m. In Fig. 5(b), the dark region representing negative FORC distribution appears below the light region of the positive FORC distribution. The dark region and the negative $H_{\rm b}$ of the positive peak in Fig. 5(b) imply that the interaction field in sample A has a magnetising effect (positive interaction).[9,20] In Fig. 6(b), there is no negative region and $H_{\rm b}$ of the positive peak is nearly zero, which indicates that there is no interaction in sample B.[9] The $H_{\rm c}$ values of the positive peaks in the FORC diagrams are equal to the coercivities obtained from hysteresis loops. The cross sections of FORC distributions at the $H_{\rm c}$ of the two samples are shown in Figs. 5(c) and 6(c). Comparing Fig. 5(c) with Fig. 6(c), one can clearly see that the variation of the interaction field in sample A is larger than in sample B. Although sample A has a positive interaction that can lead to a positive $\delta M$ peak, the large variation of the interaction field in sample A still can lead to a negative $\delta M$ peak. Even though the variation of interaction field in sample A is larger than in sample B, the negative $\delta M$ peak of sample B is higher than that of sample A. It might be due to the positive interaction field of sample A, which can reduce the effect of the variation of the interaction field on the $\delta M$ curve.

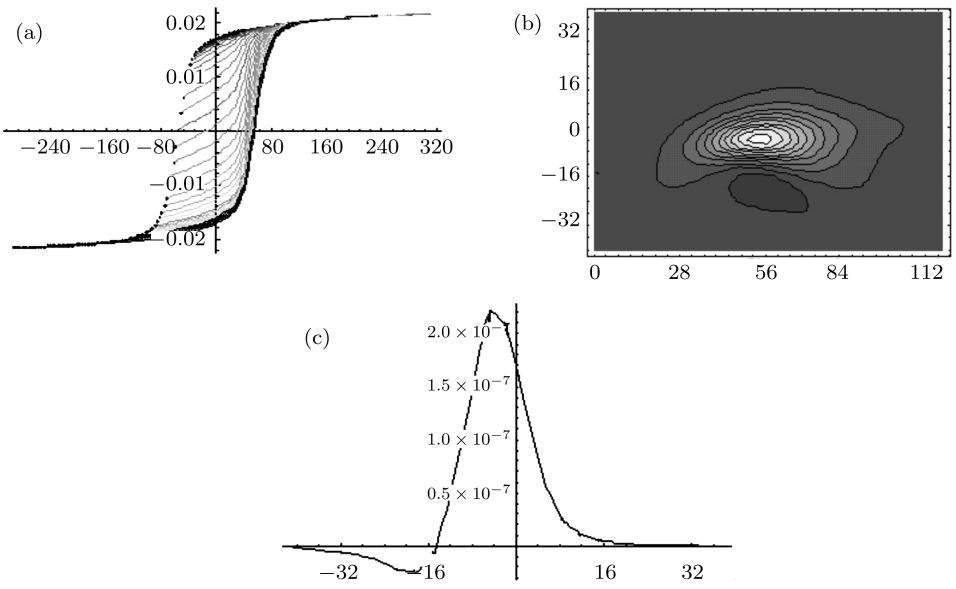



**Fig. 5.** FORC curves (a), FORC diagram (b) and cross section of FORC distribution of sample A, evaluated at $H_{\rm c} = 56$ kA/m (c).

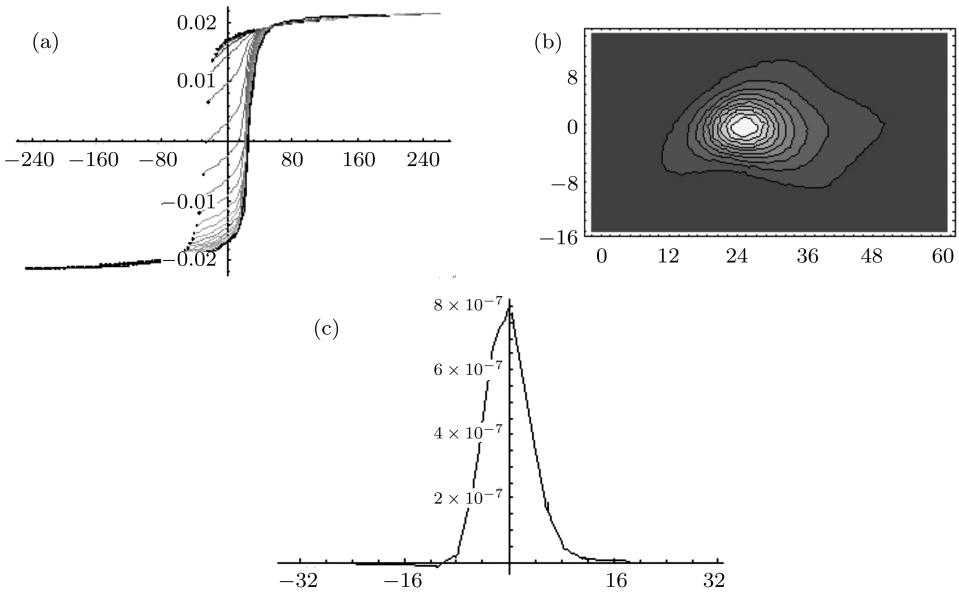



**Fig. 6.** FORC curves (a), FORC diagram (b) and cross section of FORC distribution of sample B, evaluated at $H_c = 25.6$ kA/m (c).

## 4. Summary

The FORC diagrams and $\delta M$ curves of two kinds of magnetic recording tapes have been investigated. The FORC diagrams can provide more accurate information of the interaction field and the variation of the interaction field, but the $\delta M$ curves cannot. The positive interaction field can reduce the negative $\delta M$ peak value of the sample with a larger variation of the interaction field.

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