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ORIGINAL PAPER

Data Loss and Demagnetization of Perpendicular Magnetic Recording Disk Under Sliding Contact

Lei Yang · Dongfeng Diao · Wenjing Zhan

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Abstract Data loss and demagnetization of perpendicular magnetic recording disk under sliding contact were investigated experimentally. The data loss tests of the disk against a diamond tip under normal forces (0.005–0.05 mN) and the scan of the disk with the magnetic head were sequentially carried out. Then, the demagnetization tests under normal forces (6–10 mN) were performed on the disk to examine the demagnetization behavior. After the tests, the sliding contact areas in the disk samples were observed by atomic force microscopy and magnetic force microscopy. The results showed that data loss occurred without any scratch damages on the disk and demagnetization of the magnetic medium did not occur in the data loss area. The demagnetization occurred only when the scratch depth in the disk exceeded the thickness of the diamond-like-carbon top layer. Finally, a method to study the relationship between data loss and demagnetization of the perpendicular magnetic recording disk under sliding contact was proposed and the conclusion was given that data loss of the disk was not induced by demagnetization of the magnetic medium.

Keywords Magnetic recording disk · Sliding contact · Atomic force microscopy · Magnetic force microscopy · Data loss · Demagnetization of the magnetic medium

L. Yang · D. Diao (✉) · W. Zhan
Key Laboratory of Education Ministry for Modern Design and Rotor-Bearing System, School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, China
e-mail: dfdiao@mail.xjtu.edu.cn

1 Introduction

In order to achieve high areal recording density in magnetic storage hard disk drives, perpendicular magnetic recording (PMR) disk has been developed to overcome the super paramagnetic limit of longitudinal disk [1–3]. Meanwhile, the constant upward demand for recording density of hard disk has been achieved largely by flying height reduction [4, 5]. As reported, head-media spacing has to be reduced to less than 6 nm when the areal density of the disk is 1 Tb/inch^2 [6]. However, the reduction of the flying height results in various tribological problems, including head/disk contacts during the loading/unloading process at high velocities, and contacts between the slider and asperities. Experimental results showed that the head/disk interface contacts increased abruptly when the flying height was less than a critical value [7–11]. Therefore, the mechanical reliability of the perpendicular recording disk under head/disk interface contacts becomes an important issue.

The friction heat, contact stress and scratch in the magnetic disk induced by head/disk interface contacts can lead to data loss of the disk storage. A lot of experimental and theoretical studies have been published on this subject. Suk and Jen [12] studied the effect of head/disk contacts during load/unload in terms of magnetic data loss. They found that physical damage to the disk may cause data loss. Fu and Bogy [13] observed reduction in the read-back signal amplitude after multiple load/unload cycles. Roy and Brand's [14] study indicated that frictional heat associated with contact force between the particle and disk could lead to permanent loss of data. In our previous works [15, 16], the critical conditions for data loss of the magnetic recording disk under sliding contact were investigated by experiments in combination with finite element analysis. On the other hand, the studies on demagnetization of the magnetic medium due to head/disk interface contacts have been reported a lot. Liew et al. [17] found that large surface and subsurface damage from heavy indentation and scratching resulted in large demagnetization in the magnetic recording disk. Lee et al. [18] found that plastic strain in the magnetic layers was responsible both for creating the residual mechanical scratch and for the demagnetization. Decrease of the magnetic coercivity and anisotropy in the scratch area with nanometer-depth was observed by Xu et al. [19]. Furukawa et al. [20] believed that scratch-induced demagnetization was mainly caused by plastic deformation, which resulted in grain tilt in the recording layer. Ovcharenko et al. [21] studied the effect of transient slider disk contact on magnetic erasure of the PMR disks.

However, there have been few reports discussing the relationship between data loss and demagnetization. Therefore, in this paper, data loss of the PMR disk and demagnetization of the magnetic medium under sliding contact were investigated experimentally. A drive level test apparatus with fully functional magnetic head, disk and disk drive was designed. Data loss tests of the PMR disk against a diamond tip under normal forces (0.005–0.05 mN) and scan of the disk with magnetic head were sequentially carried out. The sliding contact areas in the disk sample were observed by atomic force microscopy (AFM) and magnetic force microscopy (MFM) after the test. Then further tests under normal forces (6–10 mN) were carried out to examine the demagnetization behavior of the magnetic medium.

2 Experimental Method

2.1 Experimental Setup

Figure 1 shows the schematic sketch of the experimental apparatus. It consists of a loading system and a magnetic scanning system. A force sensor with a diamond tip was fixed on the three-axis manual stage. The normal force was applied on the magnetic disk by moving the stage, and it was removed by releasing the screw of the stage. The hard disk drive was mounted on the linear stage by a clamp apparatus. The design of the loading system insured the force sensor holding the diamond tip was horizontal. The center of the diamond tip and the center of the spindle in the hard disk drive were in line. Thus, the sliding velocity at the contact area of the disk was in the tangential direction. The linear stage was driven by the step motor with a lead screw. Computer-B recorded the normal force as well as controlled the linear stage. The magnetic head/disk scanning system was introduced to detect the damaged sectors by using a software MHDD 4.0 in computer-A, which has been used in previous work [16]. After the test, disk samples with size of 6 × 6 mm containing the sliding contact areas were cut from the tested disks. The contact areas were then observed by AFM and MFM with scanning range of 4 × 4 μm. The AFM and MFM probe scanned the area line by line in the feed direction. The number of lines in the area was chosen 512 and the scan rate was 1 Hz. The commercially available 3.5 inch hard disk based on perpendicular recording technology with the capacity of 500 Gb was used in the tests. The disk was typically composed of 4 nm thick diamond-like-carbon (DLC) top layer, 30 nm thick CoPtCr magnetic layer, 80 nm thick $Ni_{81}Fe_{19}$ soft magnetic underlayer and 10 nm thick NiP adhesion layer on the Al–Mg substrate [22, 23]. The details of the tests are given in the following sections.

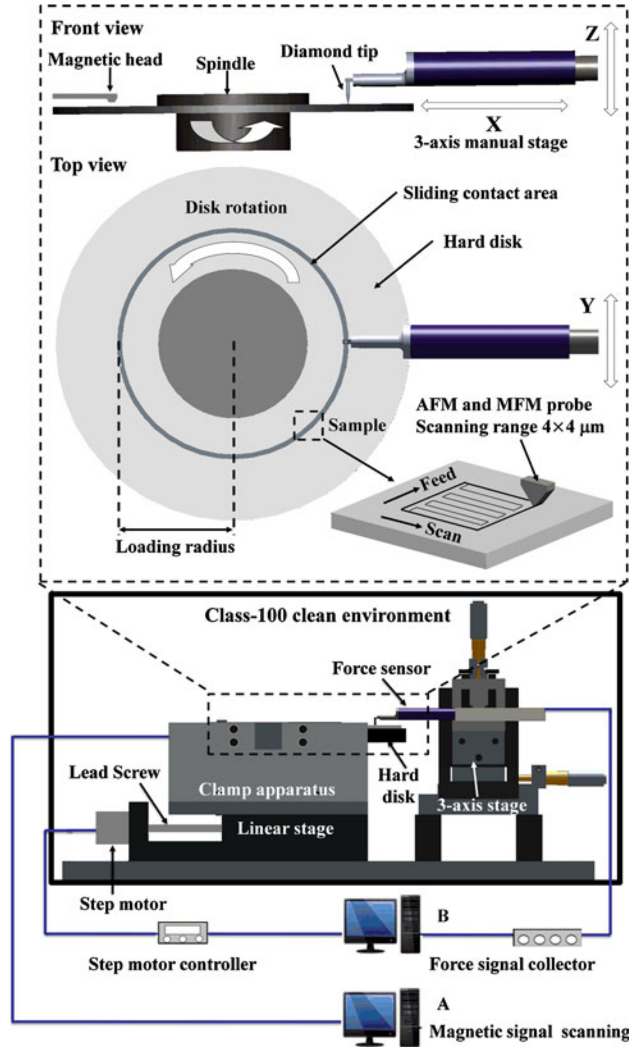

Fig. 1 Schematic sketch of the designed experimental apparatus including a loading system and a magnetic scanning system

2.2 Data Loss Test

In the data loss test, a low range force sensor (0.001–0.06 mN) was selected as shown in Fig. 2.

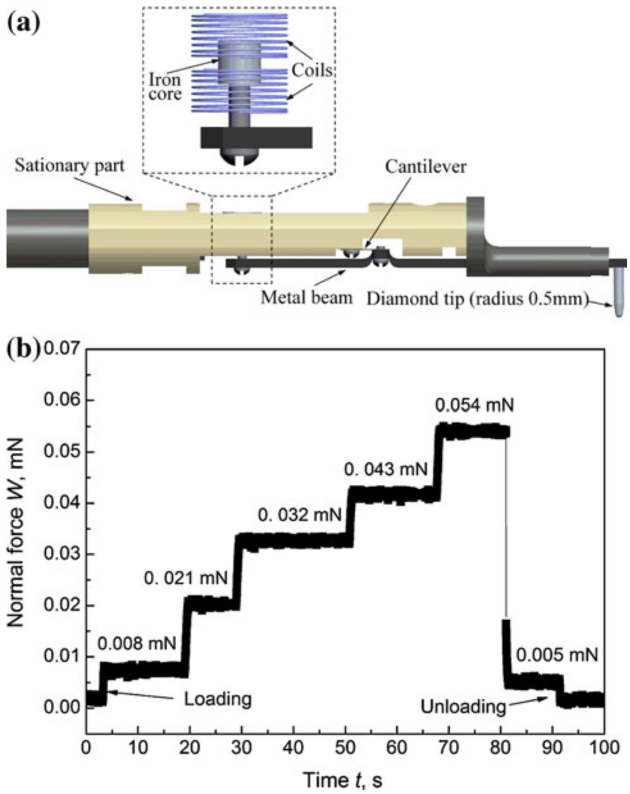

Fig. 2 The low range force sensor (0.001–0.06 mN) selected in the data loss test. **a** Structure of the sensor; **b** static loading process of the sensor

Figure 2a gives the structure of the force sensor. The metal beam was mounted on the stationary part with the cantilever. The diamond tip (radius 0.5 mm) was fixed on one end of the metal beam. The other end of the beam was attached to iron core. When the normal force was applied on the diamond tip, a micro-displacement happened to the iron core, which leads to a voltage change in the coils. The voltage change was then collected by the signal collector and recorded in computer B (as shown in Fig. 1). After calibration, we obtained the corresponding force value. The sensor had a force resolution of 0.001 mN. Figure 2b shows the loading process of the sensor. It can be seen that the sensor can appropriately load the normal force on the disk and keep steady.

Prior to the data loss test, the diamond tip was cleaned with acetone. The test was performed at room temperature with a constant relative humidity of 50 %, under class-100 clean environment. The whole disk should be scanned before loading the normal force to make sure that there were no damaged sectors in the disk. Then, the diamond tip was loaded on the disk with normal forces (0.005–0.05 mN) at loading radius ranging from 23 to 31 mm on the disk. The hard disk drive was started to work with a disk rotation speed of 7,200 rpm under which the corresponding sliding velocity at different loading radii ranged from 17.34 to 23.37 m/s. During the test, the normal force was collected by the force signal collector. After the force was unloaded, the sectors in the contact areas were sequentially scanned by the magnetic head with the software MHDD 4.0, and the numbers of the contact induced damaged sectors were recorded. Finally, the sliding contact areas in the disk sample were observed by AFM and MFM.

2.3 Demagnetization Test

In the demagnetization test, a high range force sensor (1–12 mN) was selected as shown in Fig. 3. Figure 3a gives the structure of the force sensor. One end of the metal beam was mounted on the stationary part with the cantilever. The other end of the beam was attached to the diamond tip (radius 5 μm). When normal force was applied on the diamond tip, the strain gauge stuck on the cantilever can measure the force loaded on the disk. Figure 3b shows the loading process of the sensor.

The demagnetization test was also performed at room temperature with a constant relative humidity of 50 %, under class-100 clean environment. When the test began, normal forces ranging from 6 to 10 mN were loaded on the position with loading radius of 27 mm on new disks. The hard disk drive started to work until the normal force was unloaded. The disk rotation speed was 7,200 rpm and the corresponding sliding velocity at the loading position was

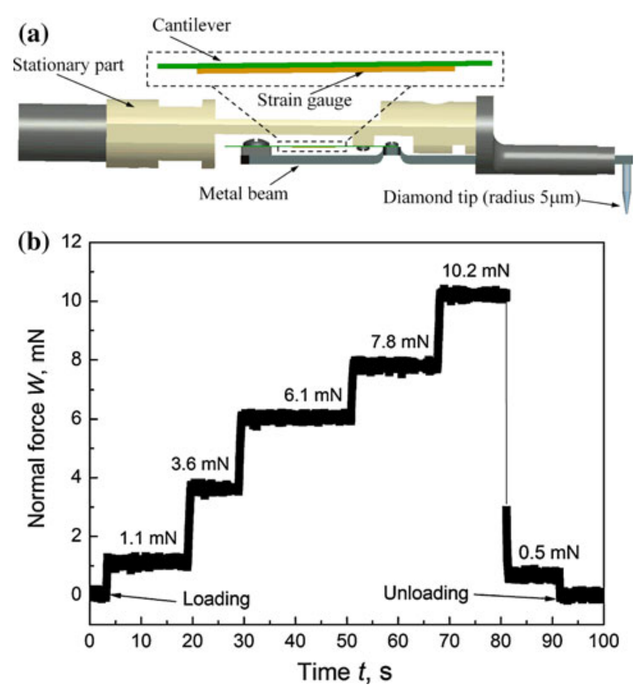

Fig. 3 The high range force sensor (1–12 mN) selected in the demagnetization test. **a** Structure of the sensor; **b** static loading process of the sensor

20.36 m/s. Then the sliding contact areas in the disk sample were observed by AFM and MFM.

3 Results

3.1 Data Loss Test Results

Figure 4 gives the critical curve in relation to normal force *W* and sliding velocity *V* for data loss of the PMR disk under sliding contact (the data loss occurred only if the damaged sectors detected by the scanning system are more than one sector as given by the author's previous work [16]). The whole area was divided into data loss zone and non-data-loss zone by the critical curve. It can be seen that data loss occurred when the normal force was above the curve. In addition, it was clear that the critical normal force for the occurrence of data loss decreased with the increasing of sliding velocity in the contact area.

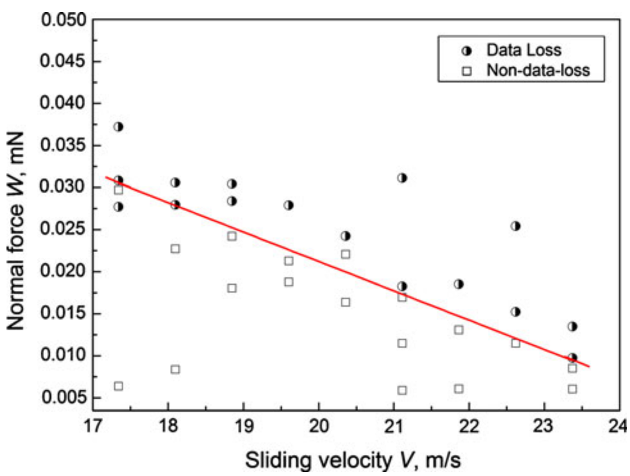

Fig. 4 Normal force versus sliding velocity and their effect on data loss of perpendicular magnetic recording disk

Figure 5 shows the typical AFM and MFM images of the data loss area in the disk under normal force $W = 0.0252$ mN and sliding velocity $V = 20.36$ m/s. As shown in the AFM image, there were no obvious scratch damages in the contact area. And the MFM image shows the magnetic bits in the contact area were clear, which indicates demagnetization of the magnetic medium did not occur in the data loss area under sliding contact. The other AFM and MFM images of the data loss results summarized in Fig. 4 were similar with that shown in Fig. 5. This is an interesting result, because most previous studies believed that data loss of the magnetic disk was caused by demagnetization of the magnetic medium. However from Fig. 5, we can recognize that data loss of the magnetic disk under sliding contact was not induced by demagnetization of the magnetic medium.

3.2 Demagnetization Test Results

Figure 6 shows the AFM and MFM images of the sliding contact areas at higher applied normal forces of 6, 8, and 10 mN with a sliding velocity of 20.36 m/s. Figure 7 shows AFM cross-sectional views of the corresponding contact areas. It can be seen that the scratch damages occurred under all of the loading conditions and the depth of the scratch increased with the increasing of the applied normal force. When the normal force was 6 mN, the depth of the scratch was about 3.3 nm, which is shallower than the 4 nm thick DLC top layer. The MFM image in Fig. 6a shows that the magnetic bits in the contact area were the same as those outside the contact area, indicating that the demagnetization did not occur at 6 mN. However, when the normal force was increased to 8 and 10 mN, the depth

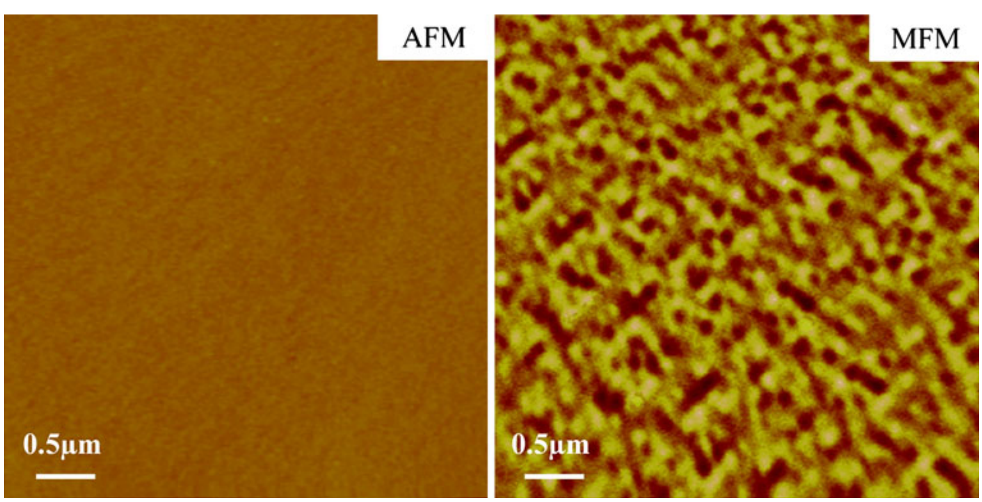

Fig. 5 AFM and MFM images of data loss area after the test ($W = 0.0252$ mN, $V = 20.36$ m/s)

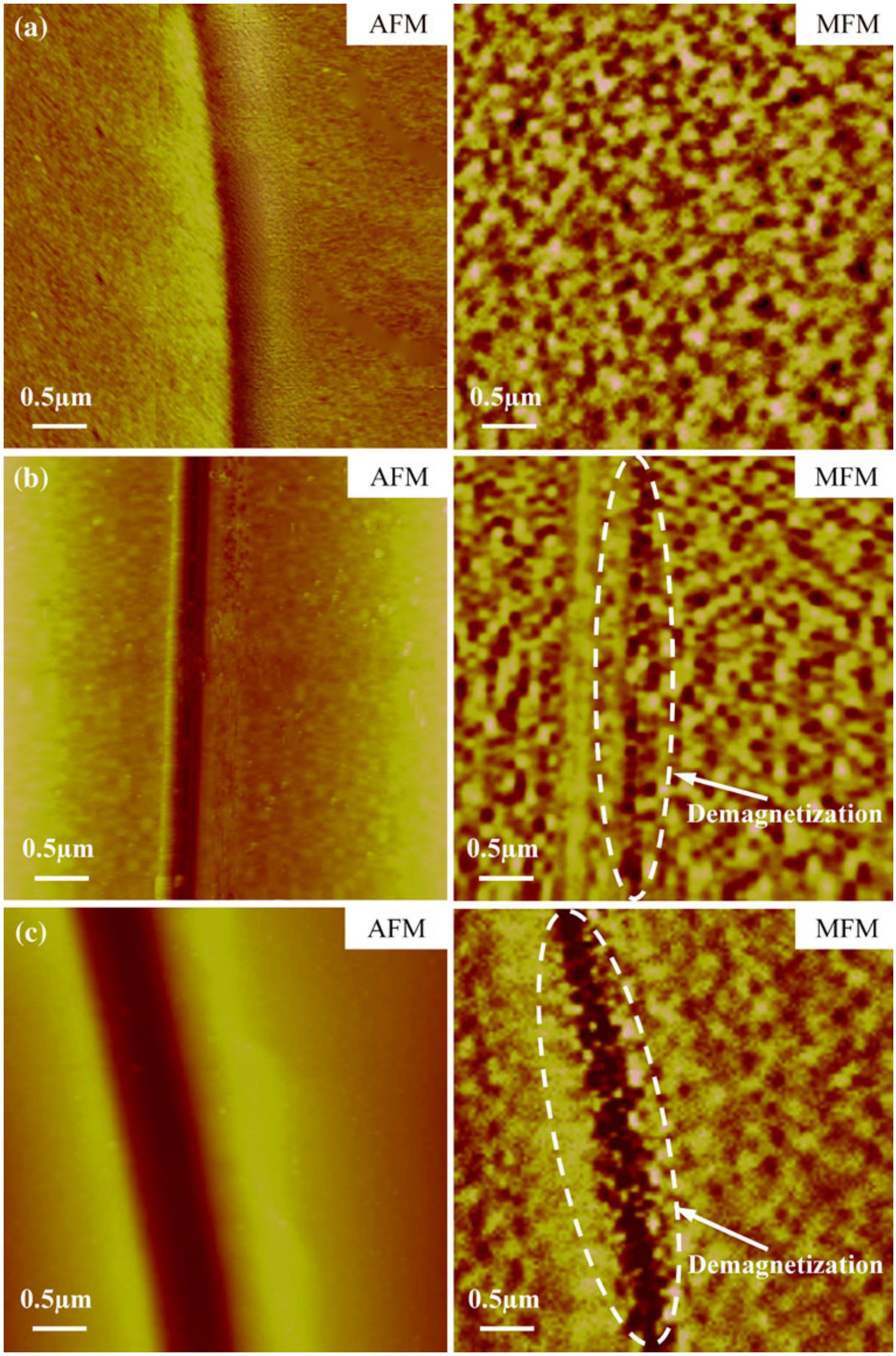

Fig. 6 AFM and MFM images of the contact areas with sliding velocity of 20.36 m/s. **a** Applied normal force 6 mN; **b** applied normal force 8 mN; **c** applied normal force 10 mN

of the scratches increased to about 13.2 and 31.6 nm, which exceed the thickness of the DLC top layer. And the magnetic bits in the contact area could no longer be clearly observed by MFM images in Fig. 6b, c, suggesting that the demagnetization occurred at 8 and 10 mN. Hence, demagnetization of the magnetic medium under sliding contact could occur only when the scratch depth in the disk exceeded the thickness of the DLC top layer. In other words, the applied normal force for the occurrence of the demagnetization was much higher than that for data loss.

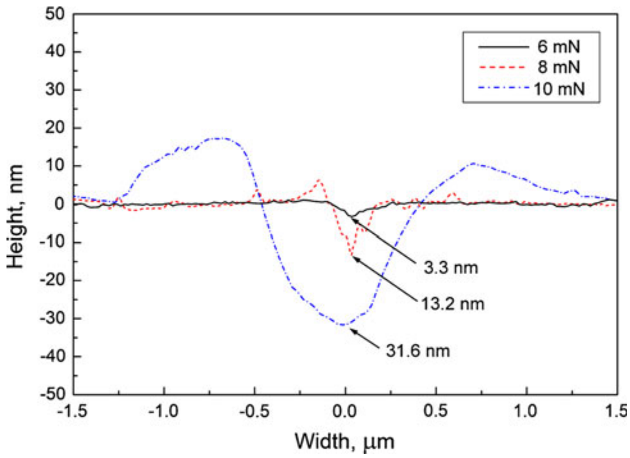

Fig. 7 AFM cross-sectional views of the contact areas with sliding velocity of 20.36 m/s at applied normal forces of 6, 8, and 10 mN

This is in accordance with the argument that data loss of the magnetic disk was not induced by demagnetization of the magnetic medium.

4 Discussions

It was clarified that data loss occurred without demagnetization of the magnetic medium. Then what is the cause for data loss of the disk under sliding contact. In our previous works [15, 16], a finite element model using thermomechanical coupling was developed to calculate the critical stress and temperature for the occurrence of data loss in the magnetic disk. Based on the model and the data loss test results, the critical compressive stress and temperature in the magnetic layer for the occurrence of data loss in this paper were 198 MPa and 327 K, respectively. We infer that the stress and flash temperature induced changes in the magnetization properties related to the data recording of the magnetic medium account for data loss of the disk.

We think that the stresses induced data loss is due to the inverse magnetostriction effect which implies the effect of stresses on the magnetization properties of magnetic medium. In Cullity et al.'s work [24], they mentioned that when the stresses were applied on the magnetic materials, the direction of the remanent magnetization was controlled by both crystal anisotropy energy and inverse magnetostriction energy. Hoshi et al. [25] found that the remanent magnetization of perpendicular recording medium decreased monotonically to about half as the compressive stress increased to 400 MPa. On the other hand, the flash temperature in the disk could also cause changes in remanent magnetization. Yuan et al. [26] noticed that the recorded data could be fully erased if the flash temperature approaches 673 K. When the heating temperature was 423 K, the remanent magnetization of perpendicular recording medium was found decreasing below 85 % in Ref. [25]. Therefore, the inverse magnetostriction effect and the flash temperature induced slight changes in remanent magnetization could lead to data loss, but can hardly cause demagnetization of the magnetic medium. Further micromagnetic simulation may be done to study these effects on data loss of the magnetic recording disk according to the calculated critical stress and temperature.

In addition, the demagnetization test results showed that demagnetization of the magnetic medium under sliding contact could occur only when the scratch depth in the disk exceeded the thickness of the DLC top layer. This is similar to the scratch test results under sliding velocity of 0.1 mm/s by Furukawa et al. [20]. In the study, they conducted a TEM cross-sectional analysis of the scratched disks and concluded that scratched-induced demagnetization of PMR media was caused mainly by plastic deformation, which includes the slippage of the crystal plane in the granular layer. Compared with the results in our study, it suggests that the plastic deformation of the magnetic medium also play an important role in demagnetization under high velocity sliding contact.

5 Conclusions

Data loss and demagnetization of the perpendicular magnetic recording disk under sliding contact have been studied. A method to investigate the relationship between data loss and demagnetization was proposed. A drive level test apparatus with fully functional magnetic head, disk and disk drive was designed. The data loss tests of the disk against a diamond tip under normal forces (0.005–0.05 mN) and the scan of the disk by the magnetic head were sequentially carried out on the perpendicular magnetic recording disk. Through the observation of the sliding contact areas using AFM and MFM, it was found data loss of the disk under sliding contact occurred without any scratch damage on the disk and demagnetization of the magnetic medium did not occur in the data loss area. Further demagnetization tests under normal forces (6–10 mN) suggested that demagnetization of the magnetic medium occurred only when the scratch depth in the disk exceeded the thickness of the DLC top layer. Finally, the viewpoint was given that data loss of the perpendicular magnetic recording disk under sliding contact was not induced by demagnetization of the magnetic medium.

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