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Investigating atomic structure of thin carbon film under mechanical stress and frictional heat generation

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ABSTRACT

Thin carbon film has been widely used as a surface protective coating for many engineering and scientific devices due to its chemical and mechanical stability. When a carbon film experiences high speed sliding contact, its material properties can be degraded by mechanical contact stress and temperature rise by friction, which thus can lead to system malfunction or failure. In this study, thin amorphous carbon film applied onto a head slider surface of hard disk drive (HDD) carried out high speed sliding contact with a single asperity defect and a bulk surface of a rotating magnetic disk. From the post-experiment analysis, it was found that the contact with a single asperity defect produced a deep scratch on the head carbon film, while the bulk surface contact generated burnishing wear on the film. After the two different types of contact test, the atomic structure of head carbon film was investigated using micro-Raman spectroscopy and X-ray photoelectron spectroscopy (XPS). It was observed that the carbon atoms in the area of deep scratch and burnishing wear clearly showed the increasing of sp^2 bonds or clusters. This implies that the head carbon film under high speed sliding contact would have experienced the graphitization process (i.e., material softening) by contact stress and frictional temperature rise. Next, the change in mechanical strength of carbon film was evaluated using the nanoscratch experiment. From the measured scratch width and depth values, it could be found that the more burnished carbon film showed the wider and deeper scratch due to the softer mechanical strength, which was consistent with the micro-Raman and XPS measurements.

1. Introduction

Diamond-like carbon (DLC) is a metastable form of carbon which contains significant sp^3-bonding fraction and lacks long-range atomic orders. Due to its superiority of mechanical strength and chemical inertness, DLC film has been widely used as a surface protective coating for many industrial products including magnetic storage devices, spur gears, bearings, razors, automotive pistons and cylinders, and biomechanical structures [1–8]. It was reported that a metal containing DLC coating (e.g., W-DLC) could reduce the wear of steel bearings and gears under heavy loading surface contact [1–3]. In automotive industry, DLC coating has been extensively applied to injection pump, cylinder liner, and camshaft drive assembly because it enables low coefficient of friction, high hardness and excellent lubrication performance [4–6]. Recently, bio-medical applications adopted thin DLC coating to protect various implanted devices such as heart valves, stents, and load bearing joints due to its excellent biocompatibility without cytotoxicity [7–9]. In the case of hard disk drives' (HDD) industry, intermittent head disk interface (HDI) contact during read/write operation can lead to critical surface damage and failure. In order to ensure the mechanical and magnetic reliability of magnetic recording head and disk, thin DLC coating is applied to their surfaces. Researchers have shown that a few nanometer thick DLC coating could significantly lower the coefficient of friction and wear behavior during HDI contact [10].

It is known that the material properties of amorphous carbon film are dependent on its deposition process, substrate materials, percentage of hydrogen or nitrogen, thickness, and so on. In particular, the mechanical strength is generally proportional to the sp^3-bonding fraction in the carbon film. With the higher sp^3-bonding fraction, the mechanical characteristics become closer to diamond. On the other hand, if the sp^2-bonding is dominant in the carbon film, its properties will be closer to graphite. Researchers have shown that the advantageous mechanical strength of DLC film can be degraded through graphitization process at high temperature condition [11–15]. Erdemir et al. [11] heated DLC films deposited onto silicon carbide (SiC) substrate increasing the temperature to 100 °C–400 °C, and then they conducted reciprocating pin-on-sample sliding tests. It was observed that the DLC film could not afford low friction coefficient beyond 300 °C, and it started showing a film delamination at the temperature of 400 °C due to the graphitization process. Yang et al. [12] measured the hardness of DLC films at high temperature condition (200 °C–600 °C), and they found that the hardness value significantly decreased when the temperature changed

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from 200 °C to 300 °C. In addition, Kalish et al. [13] studied the thermal stability of DLC films with different sp^3-bonding fractions (40%, 60%, and 80%), and it was observed that the DLC film with the higher sp^3-bonding fraction showed the initiation of graphitization process at higher temperature.

As a surface protective coating, thin carbon film has to prevent the device from surface damage by mechanical contact and corrosion failure by oxygen diffusion/penetration. In particular, when thin carbon film carries out high speed sliding contact, the contacting surface can develop significant temperature rise by frictional heat generation, which can cause thermal degradation of thin carbon film. It is known that if thin carbon film experiences thermal softening (i.e., graphitization) by high temperature rise, it will be very susceptible to mechanical contact and corrosion. Accordingly, a thermally degraded carbon film can be easily worn out by much lower contact stress value. Recently, Lee et al. [15] proposed an improved thermomechanical contact model to determine the contact stress and material temperature rise by friction during high speed sliding contact, where the contact mechanics solution was incorporated into the theory of heat transfer. However, in order to obtain more physical insights into the thermomechanical contact behavior of thin carbon film, systematic experiment as well as modeling is highly required.

In this study, the thin carbon film applied onto a magnetic recording head slider performs high speed sliding contact with a rotating magnetic disk surface, where the thin carbon film experiences mechanical and thermal degradation by stress and frictional heat generation. The change in atomic structure of thin carbon film is investigated through micro-Raman and XPS measurement. Micro-Raman spectroscopy is used to examine the extent of graphitization process of thin carbon film by high speed sliding contact, while XPS is applied to quantitatively measure the sp^2-to-sp^3 ratio. Lastly, nanoscratch experiment is performed to verify the mechanical and thermal degradation of thin carbon film by high speed sliding contact.

2. Experiment: thermomechanical degradation of thin carbon film by sliding contact

During read/write operation in HDD, thin carbon film of a head slider can experience thermomechanical damage by high speed sliding contact with a rotating disk surface, which can lead to critical head failures such as deep scratch and burnishing wear. The deep scratch failure is usually caused by the contact with disk defects or particles. Fig. 1(a) shows a typical disk defect which is buried or embedded during the manufacturing process [16]. If the defect height is taller than the head flying height or the head flying height unexpectedly becomes lower than the defect height, it can generate a critical scratch on the carbon film of a head slider. On the other hand, the burnishing wear can be produced by the bulk (or rough) surface contact between head and disk. Recently, a thermal actuation technique using a micro-heater is applied into the head design to control its active flying height, which makes thermal protrusion of read/write sensor area as seen in Fig. 1(b). Accordingly, the protruded area can have higher chance to make a sliding contact with the rotating disk surface, which can cause the burnishing wear on head carbon film.

In this study, controlled HDD level tests were performed to enable specific HDI sliding contacts, where the rotating speed of disk was 15,000 rpm. The DLC film on the head slider surface was an ion beam carbon overcoat with near zero hydrogen and nitrogen contents. To improve the adhesion strength, silicon seed layer (thickness was less than 1 nm) was applied onto the head substrate, and then the carbon overcoat was deposited. A typical carbon density for the head carbon film was 2.5–3.0 g/cm^3. In general, the ion beam deposition utilizes ion energies higher than in a conventional sputtering technique, which gives stronger ballistic impact effects of carbon ions. Accordingly, the ion beam deposition process produced very smooth and amorphous carbon film on the head slider.

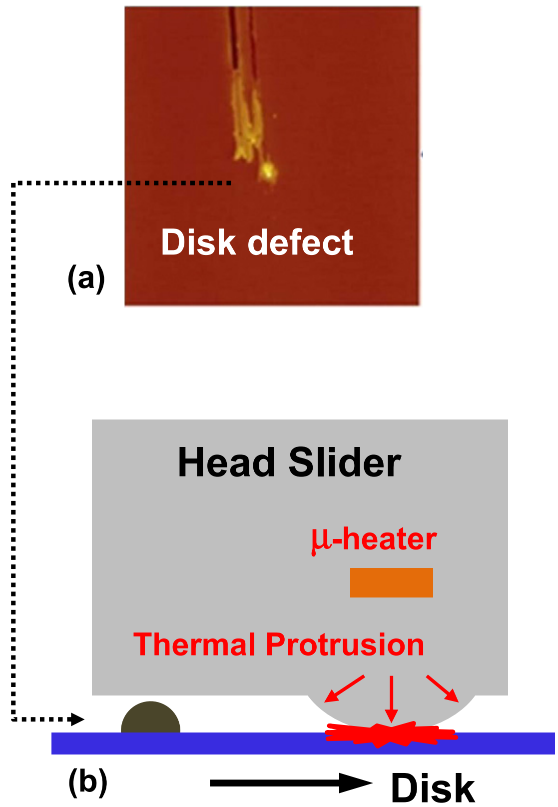

Fig. 1. Two different HDI contact modes. (a) contact with a disk defect; (b) bulk surface contact.

In experiment, first, using the servo-control function in HDD, the head slider was located at a tall disk defect position, and then it dwelled more than 12 hours to intentionally make scratch failure on the head carbon film as seen in Fig. 2(a). Second, using the heat

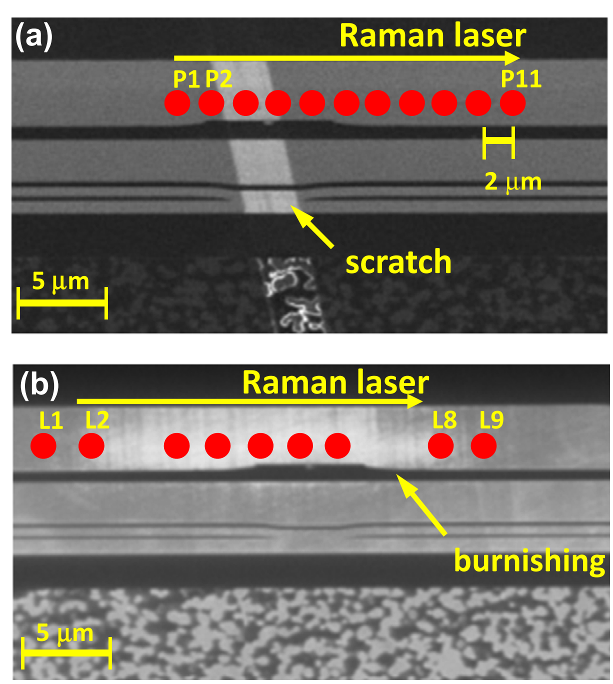

Fig. 2. Micro-Raman measurements on the (a) scratch and (b) burnishing head carbon film.