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Nanotribology properties of extremely thin diamond-like carbon films at high temperatures with and without vibration

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ABSTRACT

Extremely thin diamond-like carbon (DLC) films were deposited by filtered cathodic vacuum arc (FCVA) and electron cyclotron resonance-chemical vapour deposition (ECR-CVD) methods. The nanotribological properties of these films at high temperatures were evaluated using atomic force microscopy. At room temperature (RT), the FCVA-DLC films showed superior nanowear resistance than the ECR-CVD-DLC films. Conversely, at high temperatures in vacuum, the wear increased rapidly. The friction force of the FCVA-DLC films was low at RT in air and vacuum, but it was very high at high temperatures in vacuum. The lubricous adsorbate was removed by sliding at high temperatures. Hard brittle wear debris produced by high friction acted as an abrasive and increased the wear. In contrast, the friction force of the ECR-CVD-DLC films was low at high temperatures, corresponding to a low wear rate. Thus, the lubricous tribochemical products reduced the friction and wear. When the samples were vibrated, the wear depth of the FCVA-DLC films decreased at high temperatures, while that of the ECR-CVD-DLC films increased. Removal of the hard abrasive wear debris from the FCVA-DLC films decreased the wear by vibration, while removal of lubricous tribochemical products of the ECR-CVD-DLC films increased the wear by vibration.

1. Introduction

Tribology is a key technology in the advanced materials industry. In recent years, the development of high-density recording and the low pricing of magnetic disk drives have been realized, and further developments of new technology continue at a rapid pace. In data storage devices, diamond-like carbon (DLC) film is usually applied to magnetic recording head–disk interfaces [1]; however, atomic-scale wear and minute fluctuations in friction degrade equipment performance. Therefore, an improvement in the nanotribology of the magnetic head–disk interface is crucial for the future of the fast growing magnetic recording industry. As a result, methods for the modification of extremely thin protective films, such as DLC films on magnetic heads and disks [1–4], play an important role in realizing higher-reliability magnetic storage devices [1–3], and the surfaces of these extremely thin protective films have become critically important [2,3].

To reduce magnetic loss for increase the memory density, a reduction in the magnetic space at the magnetic head–disk interface is required, which in turn requires a reduction in the thickness of the protective film [5–7]. An extremely thin layer of protective film is applied to the medium surface and is then typically over-coated with a protective film thinner than 2 nm to realize higher-density magnetic storage. However, it is difficult to maintain mechanical durability with a 1-nm-thick deposited protective film, which amounts to approximately seven layers of carbon atoms. That is, when considering a film of the above thickness, the default properties of the atoms when subjected to friction and wear should be considered. Today, electron cyclotron resonance plasma chemical vapour deposition (ECR-CVD) [8] is used to deposit the thin films and filtered cathodic vacuum arc (FCVA) ta-C [7–9] thin films are expected to be applied to magnetic disks in the future due to its higher hardness and density.

In addition, to realize further high-density storage, such as one terabit per square inch, heat-assisted magnetic recording (HAMR) technology has been proposed in which the data is magnetically recorded on high-stability magnetic media using thermal assistance to heat the material [10,11]. For this reason, it is necessary to clarify the tribological properties at high temperature of the extremely thin DLC films used as protective films on magnetic disks and heads.

In this study, to clarify the nanotribological properties of extremely thin DLC films and their dependence on temperature, nanowear tests with and without vibration were carried out on extremely thin DLC films deposited using the FCVA and ECR-CVD methods.

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2. Experimental methods

2.1. Specimens

Extremely thin protective DLC films with thicknesses of 1, 2 and 100 nm were deposited on silicon wafers (Si (1 0 0) surfaces) using the FCVA and ECR-CVD methods [12]. Films of different thicknesses were obtained by changing the deposition time and transmission electron microscopy (TEM) analysis was used to determine the thickness of each DLC thin film. Evaluation of the deposition rate then confirmed that DLC films with thicknesses of 1, 2 and 100 nm were deposited. The composition of the films varied with the depth and was determined by auger electron spectroscopy (AES) profile depth analysis. The surface roughness (*Ra*) of the thin films was evaluated by atomic force microscopy (AFM) using a carbon nanotube tip. The difference in the surface roughness between the FCVA and ECR-CVD methods was little. The roughness was as low as 0.09–0.2 nm *Ra* and was similar to that of the Si substrate.

2.2. Nanotribological property evaluation of DLC films at high temperatures

To evaluate the dependence of the nanotribological properties on the surface temperature of the two types of extremely thin protective DLC films, nanowear tests [13–15] were performed with and without vibration using environmentally controlled AFM. A schematic of the environmentally controlled AFM apparatus is shown in Fig. 1.

A nearly 150 nm radius diamond tip fixed on a cantilever was used for the analyses. To avoid damage to and degradation of the electric parts of the AFM, the wear tests at high temperatures were performed in vacuum. The sample was placed in the chamber. First, a nanowear test was performed at room temperature (RT), nearly 20 °C in an air atmosphere. Then, the chamber was exhausted to achieve vacuum of 6×10^{-5} Pa using rotary and turbo molecular pumps. A second nanowear test was then conducted at RT in vacuum, after which the specimen temperature was changed from RT to 100, 200 °C and 300 °C in vacuum with tests carried out at each temperature using a different testing site on the sample. To clarify the nanowear mechanism for the extremely thin layers, similar vibration nanowear tests [16,17] were also performed at RT in air and at RT, 100, 200, 300 °C in vacuum. After the nanowear tests at high temperatures were completed, the temperature was returned to room temperature (RT(R)) and the nanowear test was repeated in vacuum and then in air.

The nanowear test was performed by sliding the tip with a load and scanning over a 1000 nm × 1000 nm area. The test conditions included 500–4500 nN loads and a 1.8 kHz scan frequency with and without vibration in the *Z*-direction (vertical) or *X*-direction (horizontal) to the specimen itself, as shown in Fig. 1. The vibration in the *Z*-direction or *X*-direction was added simultaneously with the scan using the force modulation mode of the AFM instrument. After the sliding test, the tested surface profiles were observed over a 1500 nm × 1500 nm area using the same tip, and the wear depth was evaluated based on the profile change. Each nanowear test was performed more than three times, and the average and typical data were considered. In this study, in order to clarify the protective ability of extremely thin DLC films for wear of the film-coated substrate, we also determined that wear depth is deeper than film thickness.

3. Results and discussion

3.1. Surface analysis of extremely thin protective DLC films

The properties of the DLC films, such as the structure, composition and actual thickness, were evaluated using Raman spectroscopy, TEM, Rutherford back scattering (RBS) and AES. From the Raman spectra of the 100-nm-thick DLC films prepared by FCVA and ECR-CVD methods, it was determined that the FCVA-DLC and ECR-CVD-DLC films have tetrahedral carbon (ta-C) and amorphous hydrogenated (a-CH) structures, respectively [12]. The FCVA-DLC (ta-C) film contains a large amount of sp^3 bonding compared with the ECR-CVD-DLC film [18–21]. The actual

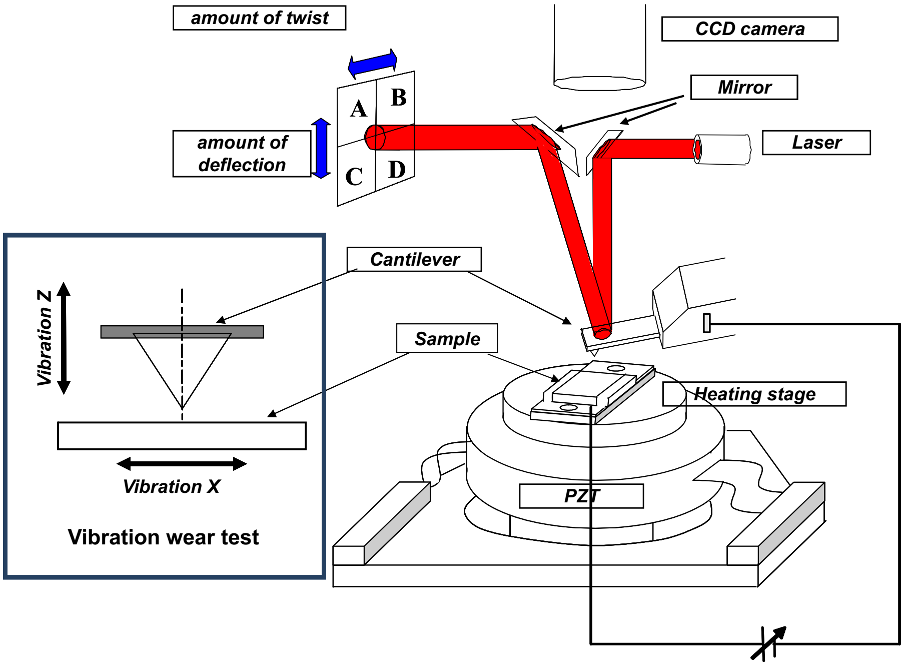

Fig. 1. Vibration nanowear test by environmentally controlled atomic force microscope.