

Effect of Hardness of Mating Materials on DLC Tribological Characteristics

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Abstract : Diamond-like Carbon (DLC) films were deposited on Si wafers by an RF-plasma-assisted CVD using CH₄ gas. Tribological tests were conducted with the use of a rotating type ball on a disk friction tester with dry air. This study made use of four kinds of mating balls that were made with stainless steel but subjected to different annealing conditions in order to achieve different levels of hardness. In all load conditions, testing results demonstrated that the harder the mating materials, the lower the friction coefficient was. The friction coefficients were found to be lower with austenite mating balls than with fully annealed martensite balls. Conversely, the high friction coefficient found in soft martensite balls appeared to be caused by the larger contact area between the DLC film and the ball. The wear tracks on DLC films and mating balls could prove that effect. Measuring the wear track of both DLC films and mating balls revealed a similar tendency compared to the results of friction coefficients. The wear rate of austenite balls was also less than that of fully annealed martensite balls. Friction coefficients decrease when applied loads exceed critical amounts. The wear track on mating balls showed that a certain amount of material transfer occurs from the DLC film to the mating ball during a high friction process. Raman Spectra analysis showed that the transferred materials were a kind of graphite and that the contact surface of the DLC film seemed to undergo a phase transition from carbon to graphite during the high friction process.

Keywords : Tribology, friction coefficient, mating ball, graphite, raman spectrum

Introduction

Diamond-like Carbon (DLC) films are one of the best anti-wear coatings for high performance mechanical elements and electric devices that require tribological enhancement and chemical stability [1-3]. Most of the previous works on DLC films have been concerned with their various properties or deposition [4-5]. However, it is also essential to take into consideration how the tribological properties of DLC films are affected by the properties of mating materials [6-9] since it is the hardness of the mating materials that is one of the important factors in determining the tribological properties of DLC films [10-13]. This paper focuses on the effects of mating materials according to their hardness on friction and wear of DLC films.

Experimental details

Tribological tests were conducted with the use of a rotating-type ball on disk friction tester with dry air. Fig. 1 illustrates the friction tester.

DLC films were deposited on Si wafers using the RF-plasma-assisted CVD method using CH₄ gas. Gas pressure and

substrate bias voltage was at 6.7 Pa and 700 V, respectively. The thickness of the deposited film was 0.4-0.5 μm , and average surface roughness was about 1 nm. Four kinds of stainless balls ($\phi = 4.8$ mm) shown in Table 1 were used as mating specimens. Martensite (FCC) structure mating balls have gone through different annealing conditions to achieve different levels of hardness. Martensite mating balls are classified into three types: hardened, medium annealed and fully annealed. The other mating ball structure is known as the austenite (BCC) structure, which is softer than a fully annealed martensite ball. The load applying to DLC films are 0.64 N, 1.28 N, 1.92 N, 3.20 N and 4.48 N for each mating ball.

Table 1. Mating ball specimens

Stainless ball type	Hardness (Gpa)	Structure or method
Hardened (SUS440C)	7.08	Martensite (FCC)
Medium Annealed	4.68	Martensite (FCC)
Fully Annealed	2.28	Martensite (FCC)
Austenite (SUS304)	1.53	Austenite (BCC)
DLC	~16.5	DLC on Si wafer by CVD

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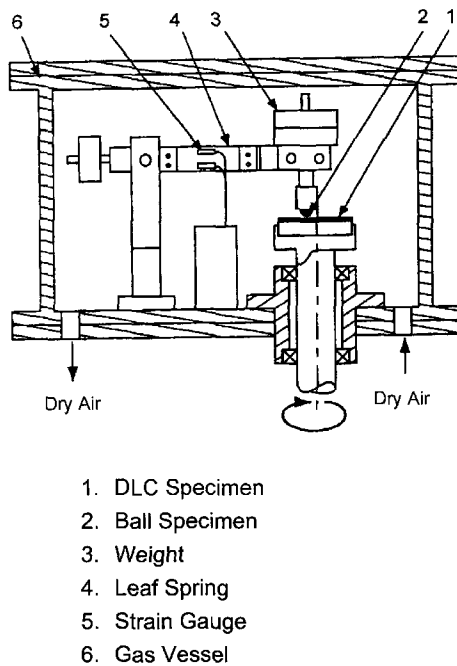


Fig. 1. Schematics of friction tester.

Results and discussion

Measurement of friction coefficients

With a rotation speed of 200 rpm, the total number of revolutions is 20,000. Fig. 2 shows some of the results of friction coefficient measurements based on a load condition of 1.92 N. The results of (a), (b) and (c), as exhibited in Fig. 2 (martensite mating balls), demonstrate how the friction coefficient increased as the level of hardness decreased. The result (b) also shows that the contact area on the friction surface widened during the friction test as the number of revolutions increased. The contact area of the softer mating ball has been observed to be wider than that of the harder mating ball. It may be concluded, as evidenced by observing the wear profiles of DLC films (Fig. 4) and wear traces of mating balls (Fig. 5), that the softer the mating balls are, the higher the friction coefficients will be in case that the structure of mating balls are same.

Fig. 3 illustrates some comparative data of several friction coefficient results, depending on the hardness of mating balls, when load conditions are at 0.64 N, 1.92 N, 3.20 N and 4.48 N. As observed under all load conditions, softer mating materials resulted in a higher friction coefficient using martensite-mating balls. This is because the contact area was enlarged during friction experiments. On the other hand, friction coefficients were lower with austenite balls. Regardless of a mating balls hardness, the maximum friction coefficient is achieved with a load condition of 1.92 N. The effects of the transfer of material between DLC films and mating balls are shown in load conditions above 1.92 N. Below 1.92 N, the increase in contact area significantly affects the friction coefficient. In this case, tendency of the friction coefficients seems to follow the ploughing effect considering on wear profiles (refer to Fig. 4)

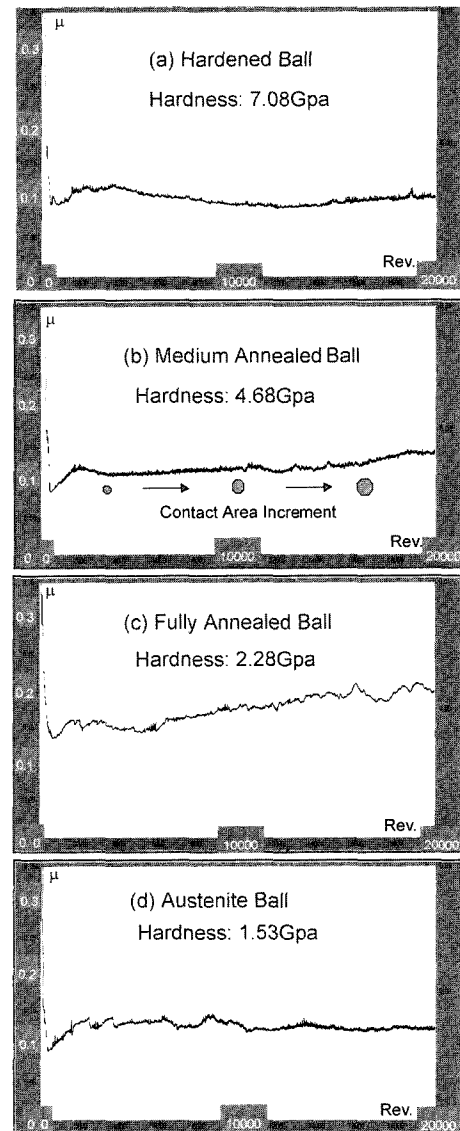


Fig. 2. Friction coefficient measurements (Load = 1.92 N).

and material properties (hard and brittle) of DLC film [7]. Above 1.92 N however, material transfer from DLC to the mating ball is a dominant factor that reduces friction coefficients as shown in Fig. 3. As the friction increases the contact surface, material transfer from DLC films appears to increase while friction coefficients seem to decrease. In this case, friction coefficients are less affected by load conditions. It is a well-known fact that both the wear rate of DLC films and the friction coefficient decrease because of the transfer of carbon-like materials from DLC films to the mating balls. DLC films undergo phase transformation during the rubbing process [8]. The Raman Spectra analysis can determine what the transferred material from the DLC films to the mating balls is.

Wear characteristics of DLC films and mating balls

Fig. 4 shows some wear track profiles in cases having a load condition of 1.92 N. The softer the mating ball, the wider the DLC film profile area is.

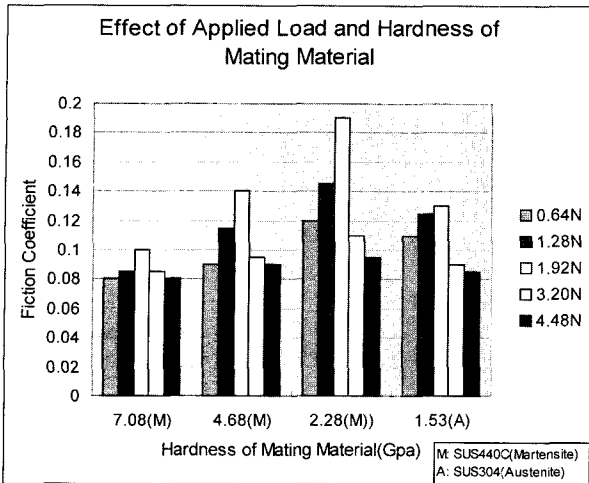


Fig. 3. Effect of hardness of mating ball and applied load.

Fig. 5 traces wear morphology of mating balls after a friction test. It also proves that the softer the mating ball, the wider the wear trace in martensite mating balls is. A wide contact profile on the DLC film and wide wear trace on the mating ball mean a wide contact area. Thus, it may be deduced that the softer the mating ball is, the wider the contact area will be. Conversely, the wear track and the wear trace profile are observably smaller with an austenite ball.

Based on the applied load and hardness of mating balls, Fig. 6 shows calculated wear rates of mating balls. As the load

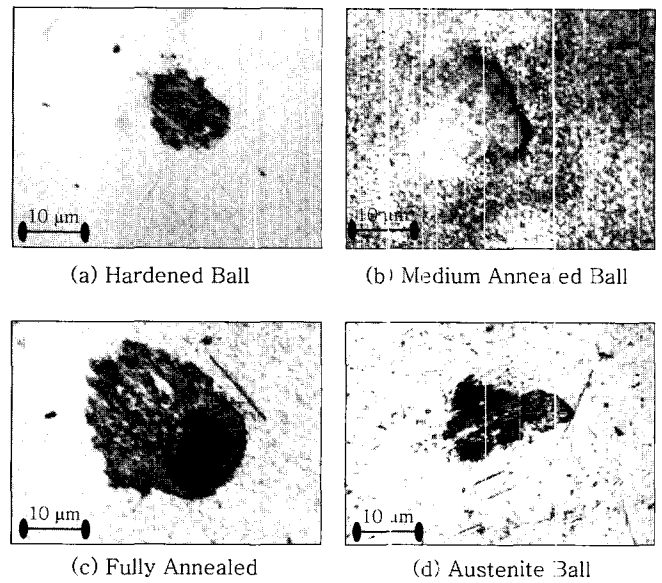


Fig. 5. Wear morphology on mating balls.

increases, wear rate of mating balls become large.

Fig. 7 shows wear rates of DLC films depending on the hardness of mating materials and the applied loads. The tendencies of wear rates are similar to the tendencies of friction coefficients in showing the peak point of wear rate. However, the load at maximum wear rate shifts to 1.28 N as mating balls soften (2.28 Gpa to 1.53 Gpa). This shift can be considered as an effect in the transfer of materials owing to an increase of

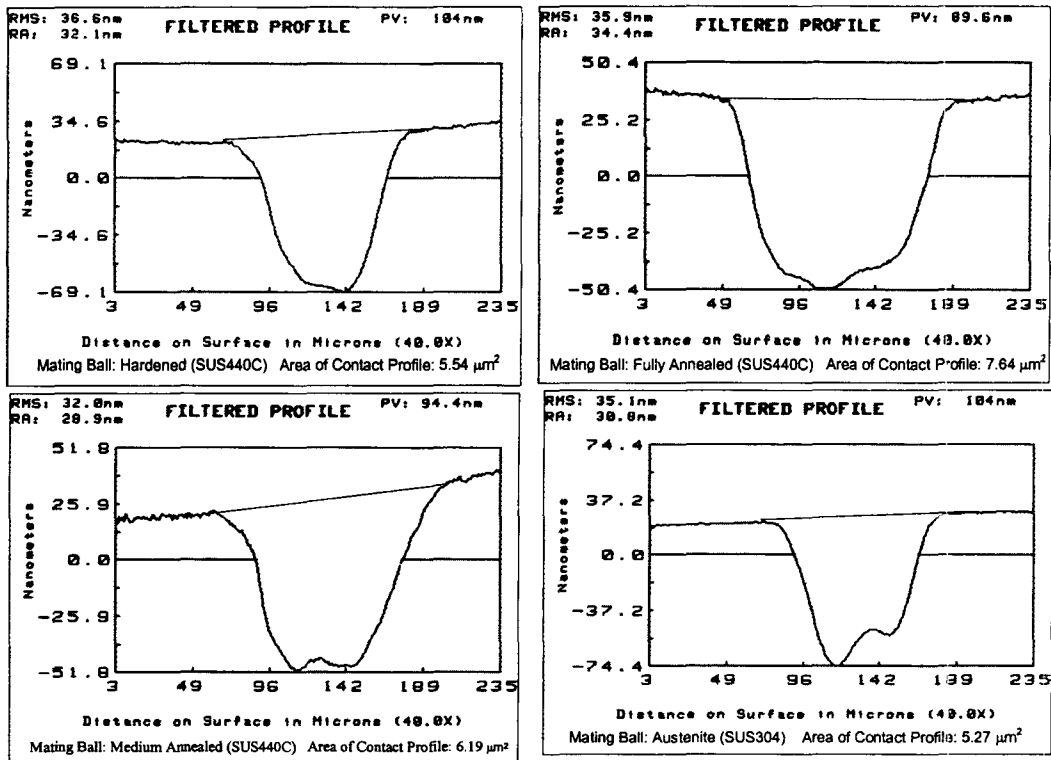


Fig. 4. Wear profiles on DLC films (Load = 1.92 N).

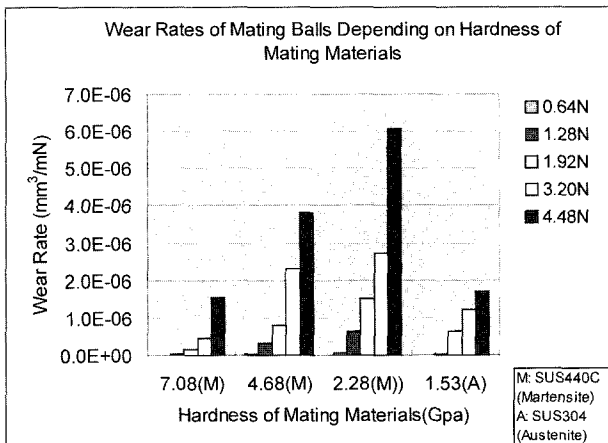


Fig. 6. Wear rates of mating balls.

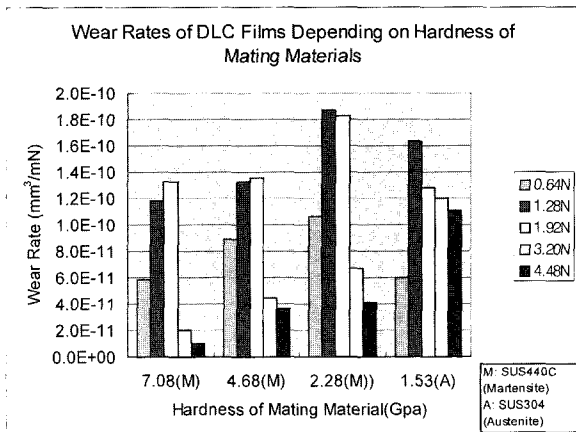


Fig. 7. Wear rates of DLC films.

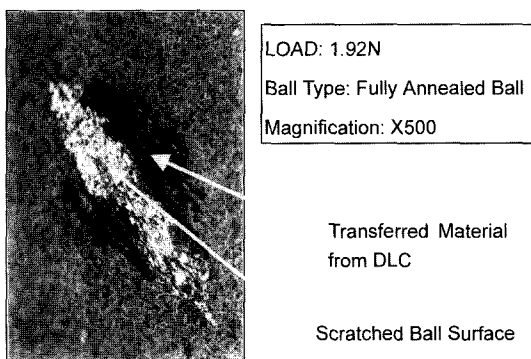


Fig. 8. Transferred material on mating ball.

friction. If friction increases, material transfer also increases while friction coefficients and wear rate decreases. At load conditions of 3.2 N and 4.48 N, wear rate decreases depending on the hardness of the mating balls and wear rates remain to be relatively smaller than light load conditions. With such heavy load conditions, material transfer could cover any mating ball regardless of its hardness.

Raman spectra analysis and transferred material

Fig. 8 shows the transferred materials on mating balls. At the

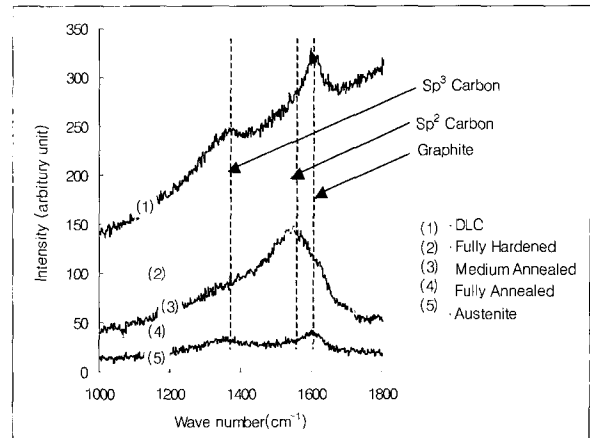


Fig. 9. Raman spectra analysis (Load = 1.92 N).

end of the experiment, the contact surface of mating balls was fully covered with transferred materials from the DLC film. In this figure, the covered material is striped for observing purpose. As shown in the figure, the DLC film and mating ball do not actually touch as transferred materials are inter-laid between them.

Fig. 9 shows the Raman Spectra analysis of transferred materials on mating balls. The first peak to be analyzed was designated as SP3 carbon according to the reference spectrum table [14]. The second was SP2 carbon. Transferred materials on mating balls that were shifted in the second peak proved to be graphite. Therefore, it may be concluded that the transferred material is graphite and that the contact surface of a DLC film is considered to have undertaken a phase transition from carbon to graphite.

Conclusion

Based on our study of the tribological properties of DLC films considering a mating balls hardness and applied loads, we conclude the following:

In using martensite-mating balls, softer mating material results in higher friction coefficient because the contact area is enlarged during friction experiment.

Below a load condition of 1.92 N, an increase in the contact area significantly affects the friction coefficient.

Above a load condition of 1.9 2N, however, material transfer from the DLC to the mating ball is a dominant factor that reduces friction coefficients.

As the load increases, area of wear trace on mating ball widens.

The maximum wear rate loads with shifts to 1.28 N as mating ball softens.

With heavy load conditions, material transfer affects all mating balls regardless of hardness.

Upon close observation, the DLC film and the mating ball do not actually touch because of the inter-laying transferred materials between them.

The Raman Spectra analysis proves that the transferred material is graphite and that the contact surface of DLC film

undergoes a phase transition from carbon to graphite.

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