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Short Communication

Modification of Thin Film Friction and Wear Models with Effective Hardness

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Abstract – Thin film coatings are commonly exploited to minimize wear and optimize the frictional behavior of various precision mechanical systems. The enhancement of thin film durability is directly related to the performance maximization of the system. Therefore, a fine approach to analyze the thin film wear behavior is required. Archard's equation is a representative and well-developed law that defines the wear coefficient, which is the probability of creating wear particles. A ploughing model is a commonly used model to determine the friction force during the abrasive contact. The equations demonstrate that the friction force and wear coefficient are inversely proportional to the hardness of the material. In this study, Archard's equation and ploughing models are modified with an effective hardness to minimize the gap between the experimental and numerical results. It is noted that the effective hardness is the hardness variation with respect to the penetration depth owing to the substrate effect. The nanoindentation method is utilized to characterize the effective hardness of Cu film. The wear coefficient value considering the effective hardness is more than three times higher than that without considering the effective hardness. The friction force predicted with the effective hardness agreed better with the results obtained directly from the friction force detecting sensor. This outcome is expected to improve the accuracy of friction and wear amount predictions.

Keywords – archard's wear model, ploughing friction model, elastic modulus, hardness, nanoindentation

1. Introduction

Thin film coatings have been widely utilized to various mechanical components to improve their wear and frictional characteristics for prolonging their lifetime[1-3].

Recently, sophisticated deposition techniques not only for improving durability of the coatings but also for functional thin films have steadily been developed in various research works and overall industries[4,5].

The quantitative assessments to guarantee the reliability of these thin films such as Archard's wear law (1953), Benjamin and Weaver model (1960), Bowden and Tabor's ploughing model (1986) and several modified models have been proposed[6,7].

It can be noticed from the previous works that such models to quantify the friction and wear characteristics of thin film have hardness term in their equations. Thus, the hardness of the film is one of the most important variables in determining the friction and wear characteristics of the films. Therefore, a more careful approach in determining the hardness values in the models should be conducted. With regards to this issue, the hardness can be varied depending on the dimension and type of the material.

Considering relatively higher mechanical properties (i.e. hardness and elastic modulus) of the underlying substrate compared to that of the thin film, nanoinden-

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tation measurement conditions should be carefully determined in order not to be affected by the substrate. According to the procedure addressed in International standard organization (ISO) 14577, the maximum penetration depth should not exceed 10% of the film thickness to measure the intrinsic value of hardness of the thin film[8]. For the copper (Cu) thin film, the hardness at the penetration depth of 50% of film thickness was over 30% higher than the hardness obtained at the penetration depth below 10% of film thickness (~3.2 GPa). The rapid increase of the hardness with respect to penetration depth due to substrate effect could cause large discrepancies during the friction and wear assumptions by using the aforementioned models.

In this work, modified friction (ploughing model) and wear (Archard's model) models with an effective hardness based on a ramp loading scratch test were proposed. The effective hardness indicates the change of hardness with respect to the penetration depth due to the effect of a hard substrate. By converting the determined hardness value to the function of hardness with respect to the penetration depth, a more accurate prediction of the amount of wear and friction force could be expected.

2. Research Methods and Results

Prior to the friction and wear tests, Cu film was deposited on a pre-cleaned Si wafer by using an RF magnetron sputter. Film thickness was 550 ± 10 nm, which was measured with an atomic force microscope (AFM) as shown in the inset of Figure 1. The hardness

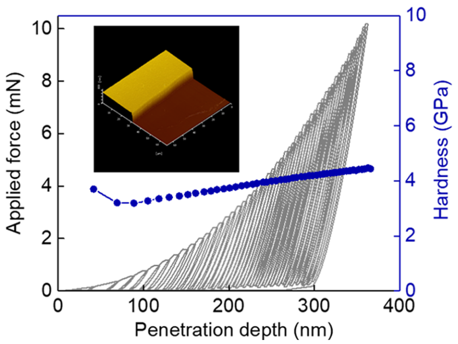

Fig. 1. Indentation force-penetration depth curve (left axis) and corresponding indentation testing hardness (H_{IT}) of 550 nm-thick Cu thin film (right axis) obtained by using CMC mode of the nano-indentation measurement. Inset is the AFM image of 550 nm-thick Cu thin film.

values with respect to the penetration depth were also measured with nanoindentation testing method. To obtain the hardness with respect to the penetration depth, a continuous multi-cycle (CMC) mode was utilized. In CMC nanoindentation testing mode, hardness measurements are conducted repeatedly on the same spot with increasing maximum load and penetration depth up to the preset indentation load. The output is given as hardness with respect to the penetration depth. The applied load was set to be increasing from 1 to 10 mN with a repeated unloading ratio of 5% of the given maximum load. Figure 1 presents the F-d curve and corresponding indentation testing hardness (H_{IT}) value with respect to the penetration depth for the 550 nm-thick Cu thin film. The H_{IT} values increased from 3.2 GPa to 4.4 GPa as the penetration depth increased from 40 nm to 365 nm, respectively. It is noted that an increase of the hardness could be obtained due to the underlying silicon (Si) substrate effect that has a 12 GPa hardness value[9].

To investigate the effect of the substrate on the friction and wear properties of thin film, a ramp loading was applied to a conical type diamond tip with 2 μm in diameter. The load was increased from 3 to 10 mN while sliding the tip for 0.5 mm on the Cu film. During the scratch test, the normal loads, frictional forces and penetration depth were monitored in real-time to assess the friction and wear properties of the film. After the tests, dimensions of the wear track were confirmed with an AFM and scanning electron microscope (SEM).

The real-time wear coefficient was evaluated by using modified Archard's model to quantify the probability of forming the wear particles during the ramp loading scratch test. The wear track was divided into finite segments with dx. Note that each segment had constant load, penetration depth and hardness. Since dx values are very small compared to the whole stroke length, the wear coefficient for each segment can be considered as an instant wear coefficient.

By applying the effective hardness in the wear model, the wear coefficient could be expressed as a function of the penetration depth as follows.

$$k = \frac{V(x)\cdot H(x)}{x\cdot L(x)} \rightarrow k_n = \frac{A(x_n)dx\cdot H(x_n)}{dx\cdot L(x_n)}$$

where V, H, x and L indicate the total wear volume, hardness, total sliding distance and applied load, respectively. In the modified model, A and dx indicate the cross-sectional area of the scratch and the segment length, respectively. As can be confirmed from the equation

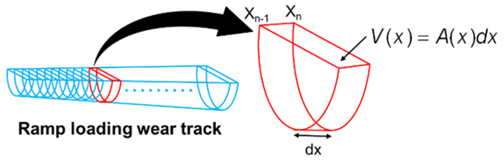

Fig. 2. Conceptual image for the modified wear coefficient calculation.

above, the wear coefficient was expressed as a function of the sliding distance. Considering that the penetration depth is a function of the sliding distance, it can be stated that the wear coefficient is dependent on the penetration depth.

The friction force from the ploughing model has been modified by converting the hardness with an effective hardness. Following is equation for evaluating the modified ploughing model.

$$F_f = \mathrm{H}(x_n)\cdot A_h \rightarrow F_f = H(x_n)\cdot w(x_n)\cdot p_d(x_n)$$

Where F_f, H and Ah are friction force, hardness and horizontal wear track area, respectively. Also, w is width and Pd is the penetration depth of the wear track. It can also be confirmed from the equation that the friction force is dependent on the effective hardness.

Figure 3 shows the optical microscope image of the scratch and SEM images of the local scratched area. The width of the wear track was increased as the scratch tip slid over the Cu thin film. Due to an increase of the contact stress as the tip slid over the Cu sample, delamination and crack of the thin film were observed.

With the measured penetration depth and width of the wear track as presented in Figure 4, the cross-sectional area of the wear track was calculated by using the equations shown in the inset of Figure 4. The penetration depth and wear area exhibited exponential behaviors along with the scratch sliding distance. It is noted that a slight decrease of the wear track cross-sectional area below 0.1 mm sliding distance could be due to the inadequate resolution of the sensor during the depth measurement.

By utilizing the hardness and wear cross-section area variation with respect to the sliding distance, the wear coefficient and friction force were acquired by using the aforementioned modified models, respectively.

Figure 5 shows the obtained wear coefficient and friction force with and without the consideration of the hardness value variations due to the substrate effect. The calculated wear coefficient with the constant hardness

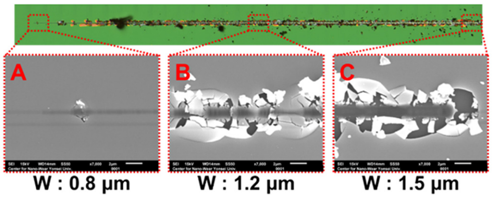

Fig. 3. Optical microscope image of the scratch track and SEM images of the local scratched area.

(3.2 GPa) increased from 3.2×10^{-4} to 4.8×10^{-2}, while that with the effective hardness incr eased from 4.5×10^{-4} to 0.1. The wear coefficient at the penetration depth of 50% of film thickness without consideration of the effective hardness was almost 3 times bigger than that was calculated with the consideration of effective hardness in the Archard's wear model.

It was also found that the analytical ploughing model with and without the consideration of effective hardness showed 15% and 60% discrepancy when compared with the results directly measured with linear variable differential transformer (LVDT) friction sensor, respectively. Note that the LVDT sensor is equipped on the scratch tester to monitor the friction force while sliding against the sample. The overall experimental results

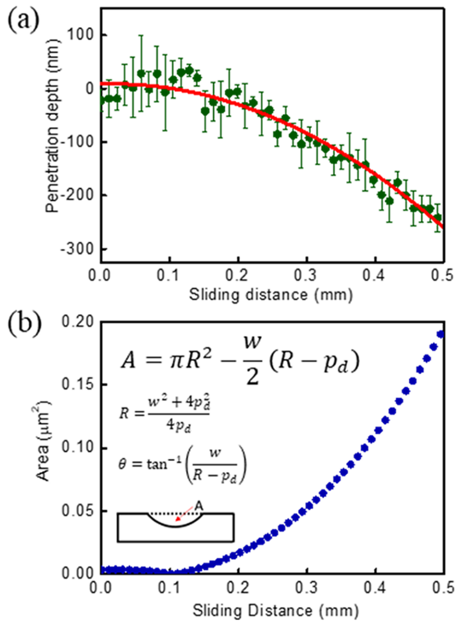

Fig. 4. (a) Measured penetration depth with respect to the sliding distance up to 0.5 mm and (b) calculated cross-section wear area along the sliding distance.

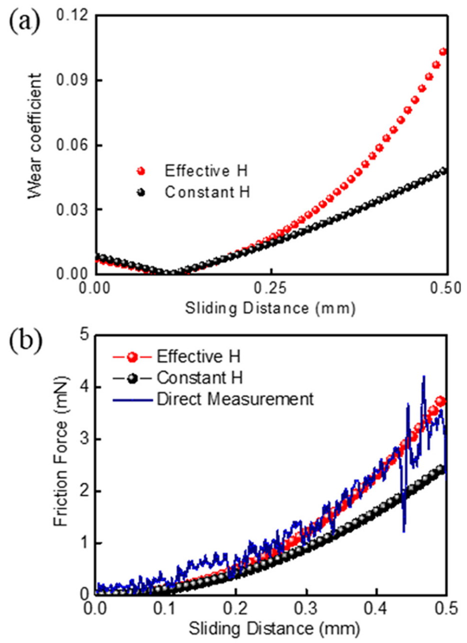

Fig. 5. (a) Wear coefficient evaluated by using Archard's wear model with constant hardness (black) and effective hardness (red). (b) The friction force evaluated by using ploughing model with constant hardness (black) and effective hardness (red). The blue line show the results of the friction force directly measured by using the LVDT friction force sensor.

revealed that the consideration of effective hardness in predicting the friction force and wear amount could be significant for the performance maximization and lifetime prolonging of the precision mechanical components.

3. Conclusions

In this work, a modified friction and wear models were established by using the effective hardness. Assessment of the modified friction and wear models was implemented with nanoindentation measurement and scratch tests of the Cu thin film that was deposited on Si substrate. The measured hardness value of Cu film on Si substrate increased by 40% with an increase of the penetration depth of the nanoindentation tip. It was shown that unlike the previous thought that the substrate effect during thin film wear test is negligible, the effect of the substrate effect on the friction and wear amount prediction was relatively large. Despite that the modified models are shown to be highly effective in determining the tribological properties of thin films, other factors such as surface roughness, surface energy, intrinsic mechanical properties and adhesion properties of the films should also be carefully considered. Overall, the result of this work will aid in understanding the fundamental friction and wear mechanism as well as providing more precise friction and wear amount predictions.

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