In Situ Raman Observation of the Graphitization Process of Tetrahedral Amorphous Carbon Diamond-Like Carbon under Boundary Lubrication in Poly-Alpha-Olefin with an Organic Friction Modifier

Hikaru Okubo1†, Chiharu Tadokoro2), Yuki Hirata3) and Shinya Sasaki3)

1) Graduate School, Tokyo University of Science, 6-3-1 Niijuku, Katsushika-ku, Tokyo 125-8585, Japan
2) Saitama University, 255 Shimo-Okubo, Sakura-ku, Saitama, Saitama 338-8570, Japan
3) Tokyo University of Science, 6-3-1 Niijuku, Katsushika-ku, Tokyo 125-8585, Japan

†Corresponding author: Hikaru Okubo (4516701@ed.tus.ac.jp)

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Abstract

The graphitization process of a tetrahedral amorphous carbon (ta-C) film under lubrication was investigated using a laboratory-built in situ Raman tribometer. The coating was lubricated with poly-alpha-olefin (PAO), PAO with an added friction modifier (FM), glycerol mono-oleate (GMO). Friction tests were carried out using a ball-on-disk setup, in which a 19-mm diameter ta-C-coated ball was loaded and rubbed against a steel disk that was immersed in a lubricant solution. In situ optical microscopy and Raman spectroscopy were used to monitor the graphitization process and wear tracks of the ta-C-coated ball. Raman analysis was conducted on the rubbed surface of the rotating ta-C-coated ball when it was located under an objective lens every three minutes during sliding. In this study, the degree of graphitization of the ta-C surface was estimated by calculating the intensity ratio of the D-peak and G-peak ($I_D/I_G$) in the Raman spectra of the ta-C film during friction tests with different lubricants. All our results suggest that the friction modifier inhibits the progression of graphitization of DLC films by reducing friction, in other words, reducing the contact temperature, and the wear progression of DLC films under boundary lubrication can be induced by graphitization of DLC surfaces at the sliding contact.

Keywords
diamond-like carbon (DLC), tetrahedral amorphous carbon (ta-C), raman observation, boundary lubrication

1 Introduction

A diamond-like carbon coating is a thin film of amorphous carbon that has $sp^2$ and $sp^3$ hybridized orbital carbon and hydrogen. In recent years, DLC coatings have been used to modify the surface of mechanical components because of their excellent tribological and mechanical properties.

Many researchers have reported the tribological properties of DLC films under various sliding conditions [1-27]. Owing to the considerable amount of research, it is well-known that the tribological behavior of a DLC film depends on various factors such as atmospheric conditions [1-6], counter-materials [7-9], and the type of lubricant [9-23]. In particular, the tribological behavior of a DLC film is governed by graphitization of the DLC film under dry sliding conditions [24-31]. Liu et al. reported that the low-friction steady-state stage of a DLC film can be related to the extensive graphitization of the transfer layers [26,27]. Erdemir et al. also reported that the low friction coefficients they obtained in long-duration tests were correlated with the formation of a graphitization layer (transfer layer) [28]. Although there have been many studies on the relationship between the graphitization and tribological properties of a DLC film under dry sliding conditions, the effects under lubricated conditions have yet to be clarified. Under lubricated conditions, the graphitization layer may be worn out and then discharged into lubricant solutions during sliding tests. Therefore, the graphitization layer cannot remain on the sliding surface, making it difficult to analyze the graphitization layer after friction tests. An “in contact” and “in situ” analysis is thus needed to clarify the effects of the graphitization on the tribological properties of DLC films under lubricated conditions. Moreover, it is expected that the lubricant additives strongly influence the graphitization process of DLC films under lubricated condition because the tribological properties of DLC films under lubricated conditions is governed by lubricant additives [9-23].

In recent years, “in contact” and “in situ (in lubro)” analytical methods have attracted the most attention to reveal the interaction between lubricant additives and tribo-materials under lubricated condition [29-34] because a surface clearing process is needed before lubricated specimens can be subjected to
vacuum-based surface analytical methods may remove important components of tribofilms on lubricated specimens. This may provide misleading understanding regarding the nature of tribofilms and the correlation between the tribofilm formation process and tribological behavior. Spikes have classified in-lubrolubricated surface analytical methods may remove important components of tribofilms on lubricated specimens. This may provide misleading understanding regarding the nature of tribofilms and the correlation between the tribofilm formation process and tribological behavior. Spikes have classified in-lrubrobiological phenomena within the rubbing contact area. However, transparent materials must be used as counterface materials, indicating that there may be cases where that differs from the actual rubbing contact. Therefore, to understand the structure of glycerol mono-oleate (GMO) is shown in Fig. 1. GMO was provided by ADEKA Co. (Tokyo, Japan). The lubricants used in this study were pure-PAO and PAO containing GMO. The lubricant with GMO had a GMO concentration of 1.0 mass%.

2 Materials and experimental details

2.1 Materials and lubricants

A bearing steel disk (diameter \( \phi = 24 \) mm; thickness \( t = 7.9 \) mm; American Iron and Steel Institute (AISI) steel grade: 52100; hardness: 700 HV) and a bearing steel ball (\( \phi = 19 \) mm; AISI steel grade: 52100; hardness: 700 HV) coated with ta-C film were used as the test specimens. The ta-C film was a commercial coating produced by ITF Co. (Kyoto, Japan) using an arc ion plating (AIP) process. The physical properties of the ta-C films were measured with a tribo-indenter (Ti950, Hysitron, Minneapolis, Minnesota, USA), through which Raman peaks were fitted with a mixed Gaussian–Lorentzian curve to determine the peak area intensity and peak position. Optical microscope images of the rubbed surface on the ta-C-coated ball were used to monitor graphitization of the ta-C films and the wear tracks on the counterface materials, indicating that there may be cases where the wear contact area. However, transparent materials must be used as counterface materials, indicating that there may be cases where that differs from the actual rubbing contact. Therefore, to understand the structure of glycerol mono-oleate (GMO) is shown in Fig. 1. GMO was provided by ADEKA Co. (Tokyo, Japan). The lubricants used in this study were pure-PAO and PAO containing GMO. The lubricant with GMO had a GMO concentration of 1.0 mass%.

2.2 In situ Raman analysis conditions

Figure 2 shows a schematic diagram of the in situ Raman tribotester. Friction tests were carried out using a ball-on-disk setup, in which a 19-mm diameter ta-C-coated ball was loaded and rubbed against a steel disk immersed in lubricant solution as shown in Fig. 2. The friction test conditions were as follows: load of 10 N (corresponding to a maximum initial Hertzian contact pressure of approximately 700 MPa); ball rotating speed of 0.04 m/s (pure-sliding condition), temperature of 100°C; addition of 5 µL of lubricant to the disk surface; test duration of 1,800 s. In this study, to confirm the repeatability of friction test results, the friction tests were repeated three times for each lubricant.

Raman spectroscopy and optical microscopy were used to monitor graphitization of the ta-C films and the wear tracks on the ta-C-coated ball. The Raman spectra were obtained using a 532-nm laser, with a maximum power output of 2.5, 5, or 25 mW (in situ Raman spectra were obtained at a laser power of 25 mW), in conjunction with an objective lens with 50× magnification. The radius of the laser spots was 6 µm. Raman analysis was conducted on the rubbed surface of the rotating ta-C-coated ball when it was located under an objective lens every 3 min during sliding. There was no laser damage to the ta-C surface under any of the conditions; the details will be discussed in section 3.1. Peak analysis was conducted using the WIRE program (Renishaw Inc., Hoffman Estates, Illinois, USA), through which Raman peaks were fitted with a mixed Gaussian–Lorentzian curve to determine the peak area intensity and peak position. Optical microscope images of the rubbed surface on the ta-C-coated ball were obtained every 6 min during sliding to measure the wear width of the ta-C-coated ball. After friction test, the disks and balls were rinsed in n-hexane after the friction tests. The wear scar of the disk and balls was evaluated by confocal laser scanning microscopy (VK-X150, KEYENCE, Japan).
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3 Results

Before analyzing the graphitization process of the ta-C films lubricated with pure PAO and PAO + GMO, the effects of laser damage and the amount of lubricant on the Raman spectrum of each ta-C-coated ball were investigated.

3.1 Effects of laser damage on the Raman spectra of the ta-C film

Figure 3 shows the Raman spectra of the ta-C-coated ball obtained at various levels of laser power (2.5, 5, 25 and 50 mW) and the peak fitting of the Raman spectra. They all show the D (1355-1430 cm⁻¹) and G peaks (1570-1584 cm⁻¹) of carbon crystals. Generally, it is well known that an increase in the ratio of the area intensity of the D band (1355 -1430 cm⁻¹) to that of the G band (1570-1584 cm⁻¹) (I\text{D}/I\text{G}) strongly relates the degree of graphitization of amorphous carbon films [10]. In this study, the degree of graphitization of the ta-C surface was estimated by calculating the \( \frac{I_D}{I_G} \) ratio. Figure 4 shows the change in \( \frac{I_D}{I_G} \) ratio as a function of laser power. In Fig. 4, there were no differences in \( \frac{I_D}{I_G} \) ratio obtained at laser power of 2.5, 5 and 25 mW. However, \( \frac{I_D}{I_G} \) ratio obtained at laser power of 50 mW are much higher than the other cases. This indicates graphitization of amorphous carbon induced by Raman laser. Since the Raman equipment used in this study was equipped with a microscope, it was possible to obtain optical images of the measurement points before and after each Raman spectrum was recorded to physically determine whether laser damage occurred. Figure 5 shows optical images of the ta-C surface before and after Raman analysis at various laser power levels. Hardly any physical changes are visible in the images except for laser power of 50 mW, demonstrating that there was little laser damage of the ta-C surface by the Raman measurements under the experimental conditions except for laser power of 50 mW. Moreover, in this study, in situ Raman spectra were obtained from the rotating ta-C coated ball, indicating that the effect of laser power on Raman spectra was eliminated or minimized. Therefore, in situ Raman spectra were obtained at a laser power of 25 mW for in situ Raman observation to obtain clear Raman peaks.

3.2 Effects of lubricant volumes on the Raman spectra of the ta-C film

Figure 6 shows the Raman spectra of PAO and PAO + GMO.

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Fig. 3 Typical Raman spectra of ta-C coated balls obtained at various laser powers of (a) 2.5, (b) 5, (c) 25 and (d) 50 mW

Fig. 4 \( \frac{I_D}{I_G} \) ratio at various laser powers of (a) 2.5, (b) 5, (c) 25 and (d) 50 mW

Fig. 5 Optical images of ta-C surfaces before and after Raman analysis at various laser powers
Peaks are observed at 1300, and 1442 cm$^{-1}$, and these peaks are attributed to $\delta$(CH$_2$) or $\delta$(CH$_3$) vibrations. Additional peaks were observed at 840-894 and 1084 cm$^{-1}$, and these peaks are attributed to $\nu$(CC) aliphatic chain vibrations. On the other hand, Fig. 7 shows the Raman spectra of a rotating ta-C-coated ball lubricated with 50 µL of PAO and a ta-C-coated disk lubricated with 5 µL of PAO. When 50 µL of PAO was used with the ta-C-coated ball, the C–H bond peaks of PAO and the D and G peaks of the ta-C film were clearly observed. On the other hand, when 5 µL of PAO was used with the ta-C-coated disk, even though the D and G peaks were clearly observed, the C–H bond peaks disappeared (Although the peaks were not observed, we visually confirmed that the ta-C-coated ball was wetted by PAO when 5 µL of PAO was used). In similar way to the case of PAO, when 5 µL of PAO + GMO was used with the ta-C-coated disk, the C–H bond peaks disappeared (these data are not shown here). Therefore, to eliminate the C–H bond peaks of PAO from the Raman spectra of the ta-C films, all friction tests were carried out with 5 µL of lubricant added to the disk surface.

3.3 In situ Raman observation results

Figure 8 shows the typical in situ Raman spectra of as-deposited and worn surfaces of the ta-C-coated ball obtained every 3 min during sliding in the friction test under lubrication with PAO and PAO + GMO. In Figs. 8(a,b), all of the in situ Raman spectra of the ta-C film lubricated with PAO and PAO + GMO show a broad band between 1000 and 1750 cm$^{-1}$, typical of amorphous carbon. The obtained spectra were divided into a “D” disordered peak (1355-1430 cm$^{-1}$) and a “G” graphite peak (1570-1584 cm$^{-1}$) by a mixed Gaussian–Lorentzian curve method. Table 2 summarizes the typical fitting results of G peak position and the $I_{D}/I_{G}$ ratio. Figure 9 shows the typical friction coefficient and $I_{D}/I_{G}$ ratio of the ta-C films lubricated with PAO and PAO + GMO as functions of sliding time. Moreover, the results of three individual friction tests under lubrication with PAO and PAO + GMO show a broad band between 1000 and 1750 cm$^{-1}$, typical of amorphous carbon. The obtained spectra were divided into a “D” disordered peak (1355-1430 cm$^{-1}$) and a “G” graphite peak (1570-1584 cm$^{-1}$) by a mixed Gaussian–Lorentzian curve method. Table 2 summarizes the typical fitting results of G peak position and the $I_{D}/I_{G}$ ratio. Figure 9 shows the typical friction coefficient and $I_{D}/I_{G}$ ratio of the ta-C films lubricated with PAO and PAO + GMO as functions of sliding time. Moreover, the results of three individual friction tests under lubrication with PAO and PAO + GMO show a broad band between 1000 and 1750 cm$^{-1}$, typical of amorphous carbon. The obtained spectra were divided into a “D” disordered peak (1355-1430 cm$^{-1}$) and a “G” graphite peak (1570-1584 cm$^{-1}$) by a mixed Gaussian–Lorentzian curve method. Table 2 summarizes the typical fitting results of G peak position and the $I_{D}/I_{G}$ ratio. Figure 9 shows the typical friction coefficient and $I_{D}/I_{G}$ ratio of the ta-C films lubricated with PAO and PAO + GMO as functions of sliding time. Moreover, the results of three individual friction tests under lubrication with PAO and PAO + GMO.
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Japanese Society of Tribologists (http://www.tribology.jp/)

GMO are also shown in Fig. 10 as examples of repeatability of the test results. For the ta-C film lubricated with pure PAO, the friction coefficient gradually decreased during the test from 0.3 to approximately 0.12. The \( I_D/I_G \) ratio of this film was extremely unstable, dramatically increasing from 0.67 to 1.84 in the initial period (the first 360 s of the test), then dramatically decreasing in the 540-720 s test period, and gradually increasing from 1.3 to approximately 2.0-2.5 in the final test period. Overall, the increasing trend of the \( I_D/I_G \) ratio of this film was observed, which correlated with graphitization and a more amorphous state than the initial one. For the ta-C film lubricated with PAO + GMO, the friction coefficient dramatically decreased during the 0.25-0.048 s test period. It should be noted that many researchers have also reported low frictional properties of ta-C films lubricated with GMO solutions [11-14,16,20-22]. On the other hand, the \( I_D/I_G \) ratio linearly increased from 0.67 to approximately 1.35 in the spectra of the ta-C film lubricated with PAO + GMO, which correlated with graphitization in similar way to the case of pure-PAO.

In Fig. 11, the wear width and \( I_D/I_G \) ratio of the ta-C film lubricated with PAO and PAO + GMO are shown as functions of sliding time. For the lubrication with pure PAO, the wear width gradually increased and eventually reached a stable value of approximately 1580 µm. On the other hand, for the lubrication with PAO + GMO, the wear width gradually increased and eventually reached a stable value of 1000 µm. These results indicate that GMO inhibited the wear progression of the ta-C film.

Figure 12 shows optical microscope images of the worn surfaces obtained every 6 min. For the lubrication with PAO, a black layer was observed on the edge of the wear track surrounded by the red dot lines in Fig. 12(a). The results of in situ Raman analysis on the black layer showed higher \( I_D/I_G \) ratio than for the as-deposited ta-C surface, and it is the maximum value in the error bar of the \( I_D/I_G \) ratio behavior at each sliding time in Fig 9. Therefore, it is assumed that the black layer was composed of the wear debris of the ta-C film and that the black layer was a graphitization layer on the ta-C surface lubricated with pure-PAO. Moreover, the black layer gradually expanded over time on the sliding surface. On the other hand, for the lubrication with PAO + GMO, even though the black layer was not observed on the edge of the wear track, the wear debris appeared to be dispersed in the solutions and on the sliding surface, as shown in Fig. 12(b). These results suggest that GMO inhibited the wear progression of the ta-C film.

Table 2: Curve fitting results of in situ Raman spectra

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>G peak position (PAO) [cm(^{-1})]</th>
<th>G peak position (PAO + GMO) [cm(^{-1})]</th>
<th>( I_D/I_G ) (PAO)</th>
<th>( I_D/I_G ) (PAO + GMO)</th>
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<td>1572</td>
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<tr>
<td>3</td>
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<td>1575</td>
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Fig. 11 Wear and $I_D/I_G$ ratio behavior under lubrication with (a) pure-PAO and (b) PAO + GMO

![Fig. 11 Wear and $I_D/I_G$ ratio behavior under lubrication with (a) pure-PAO and (b) PAO + GMO](image)

Fig. 12 Optical microscopic images of worn surfaces on ta-C coated balls lubricated with (a) pure-PAO and (b) PAO + GMO

![Fig. 12 Optical microscopic images of worn surfaces on ta-C coated balls lubricated with (a) pure-PAO and (b) PAO + GMO](image)

Fig. 13 Worn surfaces on ta-C coated balls and steel disks lubricated with (a) pure-PAO and (b) PAO + GMO after friction test

![Fig. 13 Worn surfaces on ta-C coated balls and steel disks lubricated with (a) pure-PAO and (b) PAO + GMO after friction test](image)

Fig. 13(b) [inside of the square with dotted lines in Fig. 13(b)]. On the other hand, for the lubrication with PAO, the tribofilm was not observed in Fig. 13(a). For steel disks, a spherical wear scar was observed on the steel disks for both lubricants. In similar way to the case of ta-C-coated ball, the wear diameter for PAO was higher than the case of PAO + GMO. These results indicate that GMO also inhibited the wear progression of the steel counterbody.

4 Discussion

The graphitization process of ta-C films lubricated with PAO and PAO + GMO was investigated using a laboratory-built in situ Raman tribometer. Our results suggested that graphitization of DLC films under lubricated conditions progressed over time in the same way as DLC films under dry sliding conditions [26-28]. Moreover, the progression of graphitization of the DLC films strongly depended on whether or not the existence of the friction modifier in the solution. When lubricated with pure PAO, the $I_D/I_G$ ratio of the ta-C film was extremely unstable (Fig. 9), indicating that the removal and re-formation of the graphitization layer occurred during a friction process. We believe that the behavior of changes in the $I_D/I_G$ ratio was correlated with the formation of the black layer on the sliding surface as shown in Fig. 12. On the other hand, the $I_D/I_G$ ratio of the ta-C film lubricated with PAO + GMO linearly increased. These results suggest that GMO contributed to the steady growth of the graphitization layer on the sliding surface. Actually, there is the difference between the behavior of wear particle which may contribute to the formation of the graphitization layer in pure-PAO and GMO solution as shown in Fig. 12. The graphitization layer which can be composed of the wear particles of the ta-C film formed on the edge of wear scar for pure-PAO, whereas the wear particles were dispersed well in the solution for PAO + GMO. It is well known that carbon nano-particles such as carbon nano-tube, carbon nano-onion and graphene can be dispersed in oils by the functional group-modified technics [39]. It is assumed that GMO adsorbed on the wear particles derived from the ta-C film, and GMO worked as functional group to disperse the wear particles in the solution. Therefore, GMO inhibited the aggregation of the wear particles and that might contribute to the steady growth of the graphitization layer.

Figure 14 shows the relationship between the tribological properties and $I_D/I_G$ ratio of the ta-C films lubricated with PAO and PAO + GMO. As shown in Fig. 14(a), for the lubrication with pure-PAO, the friction coefficient gradually decreased as the $I_D/I_G$ ratio increased and fell to a steady-state value at an $I_D/I_G$ ratio of approximately 1.85. On the other hand, for the lubrication with PAO + GMO, the friction coefficient gradually decreased as the $I_D/I_G$ ratio increased and fell to a steady-state value at an $I_D/I_G$ ratio of approximately 0.95. From these results, it can be seen the correlation between the stabilization of the frictional property of the ta-C/steel tribopair and the progression of graphitization. However, the other possibility of leading the low friction of the ta-C/steel tribopair is the change of the contact parameters because there is also the correlation between the wear progression of the ta-C-coated ball and the stabilization of the frictional property of the ta-C/steel tribopair lubricated with...
is the critical phase transformation temperature, $C$ is the friction-induced temperature change, $T$ for both lubricants as a function of sliding time is the difference between $I$ and the ta-C/steel contact may occur from the generation of friction. This indicates that GMO suppressed the progression of graphitization of the ta-C film lubricated with pure PAO, although the contact temperature is much higher than the graphitization temperature of DLC coatings calculated by the Clapeyron contact pressure and hydrogen content in the DLC matrix, which can be expressed by the Clapeyron law Eq. (3) [37].

$$ T = T_c \exp \left( \frac{\Delta V}{k} \right) $$

Where $\Delta T$ is the friction-induced temperature change, $\mu$ is the friction coefficient, $P$ is the applied normal load, $v$ is the sliding speed, $K_{DLC}$ and $K_{steel}$ are the thermal conductivities of the ta-C film and steel-disk, $a$ is the contact radius of the real contact area, $H$ is the measured hardness of the coating, respectively. According to the previous works [36,38], the thermal conductivity of the Cr steel ($K_{steel}$) is approximately 17 W m$^{-1}$ K$^{-1}$ [35,36]. Shamsa et al. have measured the thermal conductivity of ta-C coatings to be 3.3 W m$^{-1}$ K$^{-1}$ [38]. Le Huu et al. have reported that the graphitization temperature of DLC coating depends on Hertzian contact pressure and hydrogen content in the DLC matrix, which can be expressed by the Clapeyron law Eq. (3) [37].

According to the above equation, the graphitization temperature of the ta-C film at the Hertzian contact pressure of 700 MPa exerted by a ball-on disk set-up has been found at 200°C. Figure 15 shows the contact temperature $T$ (test temperature: 100°C) + $\Delta T(\mu)$ for both lubricants as a function of sliding time and the graphitization temperature of ta-C films calculated by the Clapeyron law. In Fig. 15, for the lubrication with PAO, the contact temperature is much higher than the graphitization temperature of the ta-C film at the Hertzian contact pressure of 700 MPa exerted by a ball-on disk set-up throughout the friction test, indicating that graphitization may easily occur. On the other hand, for the lubrication with PAO + GMO, although the contact...
temperature is higher than the graphitization temperature of the ta-C film in the initial period (from 0 to 60 s), the contact temperature is lower than the graphitization temperature of the ta-C film after the initial period, indicating that graphitization may not occur after the initial period and the contact pressure exerted by the steel disk on the ta-C coated ball was not enough to cause graphitization.

From these results, we can conclude that the friction modifier inhibits the progression of graphitization of DLC films by reducing friction (solid-solid contacts), in other words, reducing contact temperature. However, From the in situ Raman results, graphitization of the ta-C film lubricated with PAO + GMO was observed. The other possibility of leading graphitization, in other words, getting high contact stresses on the ta-C film is generation of abrasive wear particles of ta-C itself or steel counterbody (as shown in Fig. 12) proposed by Haque et al. [35]. Taking into account the applied normal load (20 N) and the contact area of spherical micro-size wear particles, the contact pressure at the contact of a wear particle and ta-C films is 50 GPa (it is assumed that the size of wear particles-derived from ta-C is 1 μm), and putting this pressure in Eq. (3), the graphitization temperature of ta-C films becomes 50°C as shown in Fig. 14. Therefore, the existence of wear particles might promote graphitization of the ta-C film even when it was lubricated with PAO + GMO.

Finally, the effects of graphitization on the tribological properties of the ta-C film were summarized in Fig. 16. As mentioned earlier, in the early stage of a friction process, the high contact temperature causes graphitization of the ta-C film at the sliding contact, and then the wear of the ta-C films progresses since the graphitic carbon layer may be softer and loosely adhered to the coating surface. In the next stage, according as the wear of the ta-C film and steel surface progresses, the wear particles can be discharged into lubricant solutions. As mentioned above, the micro-size wear particles lead high pressure on the ta-C surfaces which can result in graphitization at the sliding contact [35]. Therefore, the further wear of the ta-C film occurs at the sliding contact, and then the increment of the contact area and/or the formation of the graphitization layer lead to the low friction of the ta-C films under boundary lubrication.

All our results suggest that the optimal design of DLC films and lubricant additives that can inhibit the graphitization process of DLC films are needed to enhance the wear resistance of DLC films under boundary lubrication.

5 Conclusion

The graphitization process of the ta-C film lubricated with PAO and PAO + GMO was investigated using the laboratory-built in situ Raman tribometer. The main conclusions are as follows:

1. The progression of graphitization of the ta-C film was observed under lubricated condition. Moreover, the progression of graphitization of the ta-C film strongly depended on the type of lubricant solution used.

2. The ta-C film lubricated with pure PAO exhibited higher graphitization rate than that lubricated with PAO + GMO. These results can be explained by the high contact temperature and phase transformation temperature of DLC films. Therefore, the friction modifier inhibits the progression of graphitization of DLC films by reducing friction, in other words, reducing the contact temperature.

3. The wear progression of DLC films under boundary lubrication can be induced by graphitization of DLC surfaces at the sliding contact. Therefore, the optimal design of DLC films and lubricant additives that can inhibit the graphitization process of DLC films are needed to enhance the wear resistance of DLC films under boundary lubrication.

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References


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