Role of Water and Oxygen Molecules in the Lubricity of Carbon Nitride Coatings under a Nitrogen Atmosphere

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In this study, an experimental apparatus was developed where the relative humidity (RH) and oxygen concentration could be controlled between 0.01-10%RH and 1-100 000 ppm, respectively. This apparatus was used to study the roles of water and oxygen molecules on the friction of carbon nitride (CNx) coatings. The friction properties of Si3N4 balls sliding against CNx (Si3N4/CNx) under a nitrogen atmosphere were classified into the following three modes according to their average friction coefficients ($\mu_a$) and the stability of the friction: Mode I, $\mu_a < 0.05$ (stable); Mode II, $0.05 < \mu_a < 0.3$ (stable); and Mode III, $0.3 < \mu_a$ (unstable). To achieve a low friction coefficient (e.g. < 0.05), the optimum RH and oxygen concentration were 0.1-1.0%RH and 100-10000 ppm, respectively. Time-of-flight secondary ion mass spectroscopy (TOF-SIMS) showed that hydrogen and hydroxyl radicals derived from water molecules chemisorbed onto the worn surfaces of the CNx coatings. Raman spectroscopy suggested that the structure of carbon on the worn surfaces was different from that of the deposited CNx coating. We concluded that low friction (Mode I) arose from the water and oxygen molecules terminating carbon dangling bonds and structural changes in CNx.

Keywords: carbon nitride, super-low friction, water, oxygen, termination, structural change, nitrogen

1. Introduction

Amorphous carbon nitride (CNx), which is in the family of diamond-like carbon (DLC), is a promising coating material with high hardness and relatively low friction [1]. These properties make it a good candidate for small precision machines [2,3] where liquid lubrication cannot be applied.

Super-low friction coefficients are obtained with CNx and DLC coatings under a nitrogen atmosphere [4-7]. With super-low friction, the carbon tribolayer, whose structure has altered from that of the deposited coating, has been found on the worn surface of counterpart [8]. Structural change of the carbon [9-11] is considered to be necessary for super-low friction. However, super-low friction cannot be achieved in the presence of water or oxygen molecules [12-17], which has meant these coatings have not been used in practical applications under ambient condition.

Yoshikawa et al. reported that the CNx coatings with low friction coefficients (< 0.05) against Si3N4 balls could be achieved under ambient conditions if the coatings were heated [18]. This suggests that stable and super-low friction can be obtained regardless of the presence of water and oxygen molecules. Moreover, water and oxygen molecules could contribute to the super-low friction of CNx coatings.

In this study, the roles of water and oxygen molecules in lowering the friction coefficient of CNx coatings were clarified in detail. Guidelines are given for the conditions required to achieve a friction coefficient < 0.05 with CNx.

2. Experimental details

2.1. Deposition of CNx coatings

The CNx coatings were produced on the surfaces of substrates using an ion beam assisted deposition system (IX-30-30, HITACHI, Japan) at room temperature. Evaporation of carbon (purity 99.999%) by the electron beam was performed simultaneously with a nitrogen ion...
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The substrate was a Si$_3$N$_4$ disk (ϕ 20 mm, thickness 5 mm) or Si$_3$N$_4$ ball (ϕ 8 mm). The indentation hardness of the disk substrate was 25 GPa and the surface roughness of the disk was 12 nm in average roughness $R_a$. The substrates were cleaned with acetone, ethanol, and purified water in an ultrasonic bath before they were loaded into the deposition chamber. The Si$_3$N$_4$ disk was cleaned by nitrogen ion sputtering for 5 min to remove any adsorbed materials from the surface. The deposition rate of CN$_X$ was about 20 Å/s. The total coating thickness of CN$_X$ on the Si$_3$N$_4$ disk surface was set at 400 nm. Further information about the deposition parameters used for the CN$_X$ coatings are described in earlier research [1,19]. The indentation hardness and the surface roughness of the CN$_X$ coating on the Si$_3$N$_4$ disk were 16 GPa and 12 nm in average roughness $R_a$, respectively.

2.2. Friction tests under a N$_2$ atmosphere

To conduct the friction tests under a pure nitrogen gas atmosphere, we developed an experimental apparatus with environment control. A ball-on-disk tribometer was installed in a glove box (UN-650L, UNICO, Japan), which allowed for control of the relative humidity (RH) and oxygen concentration within the ranges of 0.01-10%RH and 1-100000 ppm, respectively. A schematic illustration of this apparatus is shown in Fig. 1. Before the friction tests, the glove box was evacuated to <5 kPa using a rotary pump, and purged with nitrogen gas for one-to-three cycles to obtain a RH of < 3%RH and oxygen concentration of < 10000 ppm. In addition to this, residual water and oxygen in the nitrogen gas in the glove box were removed by molecular sieves and a high-temperature copper catalyst, respectively. Then, the RH and oxygen concentration were adjusted when required using a nitrogen gas bubbling system (denoted as bubbler) and by the introduction of oxygen gas, respectively. A dew point meter (TK-100, TEKHNE, Japan) and an oxygen analyzer (LC-450A, TORAY, Japan) were used to monitor the dew point and oxygen concentration in the glove box, respectively. The dew point measured in this study was converted to the RH at room temperature (25°C). The CN$_X$-coated Si$_3$N$_4$ disks were moved against the Si$_3$N$_4$ balls (denoted as Si$_3$N$_4$/CN$_X$) with an applied load of 0.4 N. The rotational speeds of the disks were 60 rpm, 100 rpm, 250 rpm, and 1000 rpm.

The worn surfaces of disks and balls were observed with a confocal optical microscope (OPTELICS H1200, Lasertec, Japan). The carbon bond structures on the wear scar and the wear track of the specimens were characterized by Raman spectroscopy (NRS-5000, JASCO, Japan). The chemical states on the top surface of CN$_X$ coatings were determined using a time-of-flight secondary ion mass spectroscopy (TOF-SIMS5-100, ION-TOF, Germany).

Fig. 1 Schematic illustration of the ball-on-disk tribometer in a glove box, where the RH and oxygen concentration can be reduced by 0.01%RH and 1 ppm, respectively
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3. Results

3.1. Effect of relative humidity on friction between Si3N4 and CNX

The friction property of Si3N4 sliding against CNX under a nitrogen atmosphere with RH of 0.04 %RH and oxygen concentration of 20 ppm is shown in Fig. 2. As shown in Fig. 2(a), the friction coefficient was about 0.6-0.9 at the beginning of the sliding between the surfaces. After that, the friction changed throughout the friction tests. Figure 2(b) is a magnification of Fig. 2(a) A and shows the friction properties between cycles 4600 and 4800. Although the friction coefficient was about 0.3-0.9 at the 4600th cycle, it dropped to about 0.01 and became stable at 4700th cycle. After that, the friction coefficient increased to 0.6-0.9 and became unstable again. These results demonstrated that the Si3N4/CNX alternately showed high and low friction coefficients under a pure nitrogen gas atmosphere.

Figure 3 shows friction properties for the Si3N4/CNX under a nitrogen atmosphere at a fixed oxygen concentration with three different RHs. With a RH of 9.70%RH, the friction coefficient was about 0.1-0.3 at the beginning, and remained almost constant until the end of the friction test. With a RH of 0.20%RH, the friction coefficient dropped to 0.024 and slowly became stable after 2000 cycles, although the friction coefficient was about 0.6-1.2 at the beginning of the sliding. However, with a RH of 0.04%RH, the friction remained unstable from the beginning of the friction tests (Fig. 2). These data indicate that the RH under a nitrogen atmosphere is important in determining the friction between Si3N4 and CNX. The effect of RH on the average friction coefficient calculated between 8000-10000 cycles is shown in Fig. 4. The Si3N4/CNX resulted in a relatively low friction coefficient (< 0.05) in the RH

Fig. 2 (a) Friction property of Si3N4/CNX under a nitrogen atmosphere with RH of 0.04%RH and oxygen concentration of 20 ppm. (b) Friction property in the range between 4600-4600 cycles of the graph shown in (a) A

Fig. 3 Friction properties of Si3N4/CNX under a nitrogen atmosphere (fixed oxygen concentration condition) with different relative humidities

Fig. 4 Effect of the relative humidity on the average friction coefficient of Si3N4/CNX calculated in the range between 8000-10000 cycles under a nitrogen atmosphere with fixed oxygen concentration condition
range 0.1-1.0%RH. By comparison, the friction coefficient increased with increasing RH (1.0-10%RH) or decreasing RH (0.1-0.04%RH). This clearly indicates that there is an optimum RH for obtaining a low friction coefficient (< 0.05), and that a certain level of humidity is necessary to obtain a low and stable friction coefficient.

3.2. Effect of oxygen concentration on friction between Si_N4 and CN_X

The effect of oxygen concentration on the average friction coefficient for the Si_N4/CN_X between 8000-10000 cycles is shown in Fig. 5. Under a nitrogen atmosphere with a RH of 0.04-0.06%RH and 5000 ppm O_2, the Si_N4/CN_X showed a relatively low friction coefficient < 0.05. By comparison, the friction coefficient increased at higher (5000-100000 ppm) or lower (5000-20 ppm) oxygen concentrations. With a RH in the range 0.1-0.4%RH or 1.0-4.0%RH, the changes in the friction coefficient of the Si_N4/CN_X showed similar trends with changes in the oxygen concentration. The friction coefficient increased at higher oxygen concentrations (10000-100000 ppm) at all RH values. The oxygen concentration that resulted in a low friction coefficient (i. e. < 0.05) for the Si_N4/CN_X decreased with increasing RH (e. g. 100-10000 ppmO_2 at 0.1-0.4%RH, 30-10000 ppmO_2 at 1.0-4.0%RH). These data indicate that there is an optimum oxygen concentration that is dependent on the RH, and that a certain amount of oxygen is necessary to obtain a friction coefficient of < 0.05 under a nitrogen atmosphere.

3.3. Classification of the friction properties with changes in relative humidity and oxygen concentration

The friction properties for the Si_N4/CN_X at a rotational speed of 250 rpm under a nitrogen atmosphere with different RHs and oxygen concentrations were classified into three modes. This was according to the average friction coefficients (\(\mu_a\)) between 8000-10000 cycles and the observed friction properties. These modes were as follows: Mode I, \(\mu_a < 0.05\), stable friction; Mode II, 0.05 < \(\mu_a\) < 0.3, stable friction; and Mode III, 0.3 < \(\mu_a\), unstable friction

4. Discussion

4.1. Tribochemical reaction of CN_X with water molecules

To determine why the friction for the Si_N4/CN_X alternated between high and low friction coefficients (Fig. 2), the worn surfaces were observed under a confocal optical microscope. Under a nitrogen atmosphere with very low RH (0.03-0.05%RH) and oxygen concentration (1.5-20 ppm), the Si_N4/CN_X showed a high or low friction coefficient (Mode III), the friction tests were stopped and the wear scar on the Si_N4 ball and the wear track on the CN_X-coated Si_N4 disk were observed (Fig. 7). When the friction coefficient was about 0.50 (Fig. 7(a1)), black wear particles (> 1 \(\mu\)m thick, Fig. 8(a1)) formed on the inside and outside of the wear scar of the ball (Fig. 7(a2-1)). Although these wear particles were not observed inside the wear track of the CN_X-coated Si_N4 disk (Fig. 7(a2-2)), the wear depth of the CN_X-coated Si_N4 disk was about 700 nm (Fig. 8(a2)). Consequently, it is likely that the black wear particles were derived from...
Fig. 7  (a) Relatively high friction ($\mu_1$) observed during Mode III and the optical images of wear scar of Si$_3$N$_4$ ball ($a_{1}$) and wear track of CN$_X$-coated Si$_3$N$_4$ disk ($a_{2}$) observed during Mode III. (b) Relatively low friction ($\mu_2$) and the optical images of wear scar of Si$_3$N$_4$ ball ($b_{1}$) and wear track of CN$_X$-coated Si$_3$N$_4$ disk ($b_{2}$) observed during Mode III.

Fig. 8  (a) Surface profiles of ($a_1$) the Si$_3$N$_4$ ball and ($a_2$) CN$_X$-coated Si$_3$N$_4$ disk when Si$_3$N$_4$/CN$_X$ shows relatively high friction. (b) Surface profiles of ($b_1$) the Si$_3$N$_4$ ball and ($b_2$) CN$_X$-coated Si$_3$N$_4$ disk when Si$_3$N$_4$/CN$_X$ shows relatively low friction.
the CN\textsubscript{X} coating on the Si\textsubscript{3}N\textsubscript{4} disk. However, when the friction coefficient was about 0.04 (Fig. 7(b)), wear particles were observed only on part of the wear scar of the ball (Fig. 7(b-1)). In addition, the worn surfaces of Si\textsubscript{3}N\textsubscript{4} balls that showed high or low friction coefficients (Fig. 7) were analyzed by Raman spectroscopy (Fig. 9). For the Si\textsubscript{3}N\textsubscript{4}/CN\textsubscript{X} with a friction coefficient of 0.50, the Raman spectrum of the wear particles on the Si\textsubscript{3}N\textsubscript{4} ball (i.e. the equivalent of Fig. 7(a-1)) was similar to that of the deposited CN\textsubscript{X} coating. For the Si\textsubscript{3}N\textsubscript{4}/CN\textsubscript{X} with a friction coefficient of 0.04, the Raman spectrum also indicated that carbon present on the worn surface of Si\textsubscript{3}N\textsubscript{4}, which appeared to be covered by no transferred carbon (Fig. 9, Point 1). However, the Raman spectrum of the transferred material on the worn surface showed two carbon peaks (Fig. 9, Point 2), which could contribute to the low friction coefficient as discussed in previous research [8]. Therefore, it is likely that agglomeration and removal of wear particles, which have the same structure as the deposited CN\textsubscript{X} coating, and the formation of a low shear structure [8] also occur in friction tests under a super-dry nitrogen atmosphere.

Confocal optical microscope images and Raman spectra of the wear scars of the Si\textsubscript{3}N\textsubscript{4} balls after sliding against the CN\textsubscript{X}-coated Si\textsubscript{3}N\textsubscript{4} disks under a nitrogen atmosphere with RH of 10%RH or 0.3%RH are given in Fig. 10. With a RH of 0.3%RH and a friction coefficient of 0.024 for the Si\textsubscript{3}N\textsubscript{4}/CN\textsubscript{X} (i.e. Mode I), carbon with structural changes was observed on the worn surface (Fig. 10 (b)).
10(a1,a2), Points 1-3). However, when the Si3N4/CNX resulted in a friction coefficient of 0.18 in the 10%RH environment (i.e. Mode II), only Si3N4 was observed on the worn surface (Fig. 10(b1,b2), Points 4-6). In addition, oxidation products were observed on the Si3N4 balls, and these would increase the friction between the surfaces [14]. These results show that carbon is transferred from the CNX coating to the Si3N4 ball only with a RH of < 1.0%RH.

The worn surfaces of the CNX coatings were also analyzed by TOF-SIMS to clarify the chemical state of the coating and the effect of water molecules on the friction of the CNX coatings. Before the friction test, deuterated water (D2O (2H2O), Cambridge Isotope Laboratories, Inc, United States) was introduced into the glove box, and any H2O contained in the nitrogen gas was replaced with D2O so that chemical adsorption of H2O during friction test could be distinguished from natural adsorption from the atmosphere. A CNX-coated Si3N4 ball and two CNX-coated Si3N4 disks were prepared for this experiment. One of the disks was used in the friction test and the other was not, and the results were compared between the two disks. Figures 11 and 12 show TOF-SIMS images of the wear track on the CNX-coated Si3N4 disk and the wear scar on the CNX-coated Si3N4 ball, which gave a friction coefficient of 0.015 under a nitrogen atmosphere (500 ppmO2, < 5%RH). Figure 11(a1-c1) shows the natural adsorption of 2H- (Fig. 11(a1)), O2H- (Fig. 11(b1)), and CNO- (Fig. 11(c1)) on the CNX coatings during the friction test. These results revealed that little 2H2O adsorbed onto the surface of the CNX coating. TOF-SIMS images (Fig. 11(a2,b2)) showed that 2H- and O2H- adsorbed onto the wear track of the CNX coating. Adsorption of 2H- and
O\(_2\)\(^{-}\) was also observed on the wear scar of the CN\(_{x}\)-coated Si\(_3\)N\(_4\) ball (Fig. 12(a,b)). Therefore, \(^{2}\)H\(^{-}\) and O\(^{2}\)H\(^{-}\) were chemically adsorbed on the worn surface. These results suggest that water molecules in the nitrogen gas dissociate into H\(^{-}\) and OH\(^{-}\) because of the friction between the surfaces, and these species then chemisorb onto the CN\(_{x}\) coating when the CN\(_{x}\) has a low friction coefficient (< 0.05).

4.2. Tribochemical reaction of CN\(_{x}\) with oxygen molecules

Confocal optical microscope images and Raman spectra of the wear scars for experiments with friction coefficients < 0.05 or > 0.05 (Fig. 5) are given in Fig. 13. For the Si\(_3\)N\(_4\)/CN\(_{x}\) that gave a relatively low friction coefficient with 1100 ppmO\(_2\) and 0.32%RH (Mode I), carbon with structural changes was observed on the worn surface of the ball (Fig. 13(a), Points 1 and 2). However, for the Si\(_3\)N\(_4\)/CN\(_{x}\) that gave a relatively high friction coefficient with 70 ppmO\(_2\) and 0.24%RH (Mode II), the structure of carbon on the worn surface was similar to that of the carbon in the deposited CN\(_{x}\) coating (Fig. 13(b), Point 3). Notably, the structure of carbon on the wear scar changed from that of the carbon in the deposited CN\(_{x}\) in a high-oxygen environment (1100 ppm), although the carbon was transferred from the CN\(_{x}\) coating to the Si\(_3\)N\(_4\) ball regardless of the oxygen concentration.

To elucidate the role of chemisorption of oxygen molecules, friction tests for Si\(_3\)N\(_4\)/CN\(_{x}\) under a nitrogen atmosphere (20-60 ppmO\(_2\)) were conducted at different rotational speeds (Fig. 14). The average friction coefficient decreased as the rotational speed was reduced from 250 to 60 rpm. Generally, the amount of adsorbed oxygen molecules increased as the rotational speed of the disk decreased, which suggests that the average friction coefficient decreases with increasing adsorption of oxygen molecules on the CN\(_{x}\) coating. The Raman spectrum of the worn surface after the friction test at 60 rpm, which gave a low friction coefficient (< 0.05), is given in Fig. 15. Carbon with structural changes was observed on the worn surface of the Si\(_3\)N\(_4\) ball. Compared with the Raman spectrum of the worn surface obtained in the relatively high friction experiment (70 ppmO\(_2\), 250 rpm, Fig. 13(b)), the structure of the carbon likely changed because of the decrease in the rotational speed and an increase in the adsorption of oxygen molecules. Therefore, a tribochemical reaction of the
CNx coating with oxygen molecules promotes structural changes in the carbon that is transferred onto the Si3N4 ball.

To further clarify the role of oxygen chemisorption on structural changes in the carbon from the CNx coating, friction experiments were performed with Si3N4 disks coated in CNx and Si3N4 balls in environments with various oxygen concentrations. Then the worn surfaces of the CNx coatings on Si3N4 disks were analyzed by Raman spectroscopy (Fig. 16). In the 1 ppmO2 environment, the carbon on the worn surface had the same structure as that in the deposited CNx coating. By contrast, under ambient air and under a dry oxygen atmosphere, structural changes were observed in the carbon in the center of the wear tracks. Although the Si3N4/CNx resulted in a friction coefficient of > 0.05 in each environment, the structure of the carbon changed from that in the deposited CNx coating on disk as the oxygen concentration increased. Taking into account the TOF-SIMS results, which provided evidence that oxygen in nitrogen gas chemisorbed onto the worn surface of the CNx-coated Si3N4 disk (Fig. 11(c2)) and Si3N4 ball (Fig. 12(c)), these experiments have shown that adsorption of oxygen molecules onto the CNx coatings and the triboreaction results in structural changes in the carbon on the worn surface of the Si3N4 ball and CNx coating. These structural changes contribute to the super-low friction [8].

4.3. The roles of water and oxygen molecules in determining the friction of the CNx coating

Optimizing the amounts of water and oxygen molecules is a key factor in obtaining stable and low friction with CNx coatings. The amounts of water molecules and oxygen molecules chemisorbed in triboreactions are very important in determining the friction of CNx coatings. With the optimum amount of water molecules in the nitrogen gas (e. g. 0.1-1.0%RH; Mode I), the water molecules constantly chemisorb onto the surface of CNx coatings because of the friction, and result in a low and stable friction coefficient. However, when the water content of the nitrogen gas was low (< 0.1%RH, Mode III), the carbon that was transferred to the Si3N4 ball, reacted directly with the carbon in the CNx coating and C-C bonds formed. This led to wear of the CNx and high friction (Fig. 2, Fig. 7(a1)). When the water content of the nitrogen gas was high (> 1.0%RH, Mode II), friction increased because the structure of transferred carbon is not maintained and oxidation products formed on the surface of the Si3N4 ball [14]. Kubo et al. used a tight-binding quantum chemical molecular dynamics simulation and found that hydrogen termination of DLC or CNx coatings and hydroxyl termination of DLC contributed to low friction [20-23]. They also reported that non-hydrogen-terminated DLC coatings display very high friction because of the formation of C-C bonds [22]. In this study, hydrogen and hydroxyl derived from

![Figure 14](image1.png)

**Fig. 14** Effect of the rotation speed on the average friction coefficient of Si3N4/CNx calculated in the range between 8000-10000 cycles under a nitrogen atmosphere with RH of 0.2-0.3%RH and oxygen concentration of 20-60 ppm

![Figure 15](image2.png)

**Fig. 15** (a) A optical image of wear scar on Si3N4 ball and (b) Raman spectra, which gives low friction coefficient < 0.05 under a nitrogen atmosphere (0.2-0.3%RH) with oxygen concentration of 20-60 ppm at a rotation speed of 60 rpm
the water molecules terminated the carbon dangling bonds and suppressed the formation of C-C bonds [22,23]. This resulted in the formation of a low shearing interface where only Van der Waals forces [24] occurred between the CNX coatings, and this reduced the friction coefficient to below 0.05. Therefore, we concluded that the tribochemical reaction of the CNX coatings with the water molecules resulted in the stable and low (< 0.05) friction coefficient.

Generally, it has been noted that wear of CNX and DLC coatings increases with increasing oxygen levels because of the reactions that occur between the coating and the oxygen molecules [13,14]. Xu et al. reported that the tribochemical reactions of DLC coatings in dry air led to oxidation of carbon, resulting in the formation of CO2 [25]. The structure of worn CNX changes from that of the deposited CNX because of desorption of nitrogen atoms inside the coating [10]. In consideration of this, the desorption of the surface carbon because of tribochemical reactions with oxygen molecules, which result in formation of CO2, can reorient the carbon networks on the surface and lead to the structural changes observed in the CNX coatings. Thus, the tribochemical reaction of carbon with oxygen molecules in nitrogen gas promotes structural changes in the CNX coatings.

As mentioned above, optimization of the water and oxygen levels leads to tribochemical reactions that result in structural changes in the carbon on the worn surface and termination of carbon dangling bonds by hydrogen and hydroxyl radicals. Therefore, certain humidity and oxygen concentration considered are necessary to achieve stable and low friction (Mode I). This study focused on the friction mechanism under a nitrogen atmosphere with relatively low RH and oxygen concentrations. The conditions required to form a low shearing interface between CNX coatings under other conditions will be investigated in future studies.

5. Conclusions

In this study, an experimental apparatus was developed where the relative humidity (RH) and oxygen concentration could be controlled within 0.01-10%RH and 1-100000 ppm, respectively. Friction tests for CNX-coated Si3N4 disks against Si3N4 balls were conducted in this apparatus, and the roles of water molecules and oxygen molecules on the stability of the friction coefficient were investigated under a nitrogen atmosphere. The main conclusions were as follows:

1. For the Si3N4/CNX at a rotational speed of 250 rpm, the friction properties were classified into three modes according to the average friction coefficient ($\mu_a$) between 8000-10000 cycles and the stability of the friction. These modes were as follows:
   - Mode I, $\mu_a < 0.05$, stable friction;
   - Mode II, 0.05 < $\mu_a$ < 0.3, stable friction; and
   - Mode III, 0.3 < $\mu_a$, unstable friction.

2. To obtain a low friction coefficient (< 0.05, Mode I), the optimum RH range was 0.1-1.0%RH and the optimum oxygen concentration range was 100-100000 ppm.

3. When the CNX coating showed a friction coefficient below 0.05, hydrogen and hydroxyl radicals derived from water molecules in the nitrogen gas chemisorbed onto the worn surface. The water molecules promoted termination of carbon dangling bonds on the CNX coating.
(3) When the CN$_X$ coating showed a friction coefficient $< 0.05$, the structure of carbon on the worn surface of the Si$_3$N$_4$ ball was different from that of the deposited CN$_X$ coating. Oxygen molecules in the nitrogen gas promoted structural change in the CN$_X$ coating.

(4) The Si$_3$N$_4$/CN$_X$ alternately showed high and low friction coefficient under a nitrogen atmosphere with a RH of 0.04%RH and oxygen concentration of 20 ppm.

(5) At high RH and oxygen concentration values (>1.0%RH, > 10000 ppm), the carbon in the CN$_X$ coating was not transferred and oxidation products were generated on the surface of the Si$_3$N$_4$ ball. This resulted in a high friction coefficient of $> 0.05$.

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References


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