

A Study on Friction and Wear Properties of Tetrahedral Amorphous Carbon Coatings on Various Counterpart Materials

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Abstract – This research addresses the improvement of tribo-systems, specifically regarding the reduction of friction and wear through tribo-coupling between tetrahedral amorphous carbon (ta-C) with different types of counterpart materials, namely bearing steel (SUJ2), tungsten carbide (WC), stainless steel (SUS304), and alumina (Al₂O₃). A second variable in this project is the utilization of different values of duct bias voltage in the deposition of the ta-C coating – 0, 5, 10, 15, and 20 V. The results of this research are expected to determine the optimum duct bias and best counter materials associated with ta-C to produce the lowest friction and wear. Results obtained reveal that the tribo-couple between the ta-C coating and SUJ2 balls produces the lowest friction coefficient and wear rate. In terms of duct bias changes, deposition using 5 V produces the most optimum tribological behavior with lowest friction and wear on the tribo-system. In contrast, the tribo-couple between ta-C with a WC ball causes penetration through the coating surface layer and hence high surface delamination. This study demonstrates that the most effective ta-C coating duct bias is 5 V associated with SUJ2 counter material to produce the lowest friction and wear.

Keywords – filtered cathodic vacuum arc (FCVA), friction, wear, ta-C coating, tribo-coupling

Explanation for symbols

P_m : Mean contact pressure (Pa)
 N : Normal load (kg)
 a : Diameter of contact area (m)
 R : Ball radius (m)
 ν_1 : Ball Poisson's ratio
 ν_2 : Disc Poisson's ratio
 E_1 : Ball Young's modulus (GPa)
 E_2 : Disc Young's modulus (GPa)

1. Introduction

Tetrahedral-amorphous carbon (ta-C) is a type of hydrogen-free diamond-like carbon (DLC). It has received great interest among researchers owing to its distinctive properties. A ta-C coating consists of up to 85% sp³ bonded carbon configuration, causing it to possess higher hardness and elastic modulus compared to other types of coatings. Therefore, a ta-C coating can be applied in different fields, including the automotive industry, manufacturing industry, and biomedical applications. These applications involve a tribo-coupling process between a ta-C-coated surface and a counterpart surface. Improvement in machine reliability, enhancement in machine productivity, and extension of system longevity are the main concerns

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addressed in the tribology field [1-2].

Thus, friction and wear behavior are particularly important in this context. Among the various types of materials, bearing steel (SUJ2), tungsten carbide (WC), SUS304 stainless steel, and alumina (Al_2O_3) are chosen as counterparts of the ta-C coating in this study owing to their conventional use in different industries.

In this study, ta-C-coated samples are produced by changing the duct bias voltage via the filtered cathodic vacuum arc (FCVA) method, and their tribo-coupling effects are tested with various balls (SUJ2, WC, SUS304, and Al_2O_3 material). The objective of this study is to determine the most effective duct bias and best counterpart material associated with ta-C to produce the lowest friction and wear behavior.

2. Experimental Procedure

2-1. ta-C Coating by FCVA

A ta-C coating was applied to a tungsten carbide cobalt (WC-Co) substrate by FCVA. The substrate size was limited to 15.5 mm × 15.5 mm × 4.5 mm. Prior to deposition, ultrasonic cleaning was performed on the substrate to remove surface impurities. In this research, the ta-C coater shown in Fig. 1 was used for deposition.

As a controlling parameter for this research, samples were deposited under a duct bias of 0, 5, 10, 15, and 20 V. The substrate bias induced was 80 V.

The duct bias is one of the experimental parameters, while the plasma central voltage is a function of plasma density.

Fig. 2 summarizes the concept of the duct bias. As the duct bias decreases, the width of the plasma beam increases in the FCVA ductal wall, but the ion energy decreases. Conversely, as the duct bias increases, the width of the plasma beam decreases in the FCVA duct wall; however, the ion energy increases, which is a useful method to change the mechanical properties of a tribo-system.

The system was vacuumed before the coating pro-

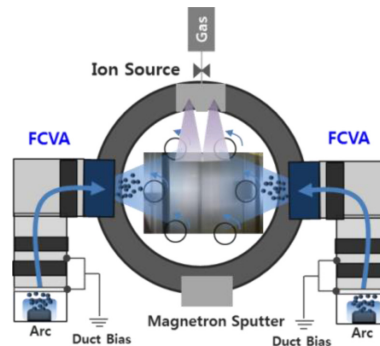


Fig. 1. Schematic illustration of ta-C coating with 90° type filtered cathode vacuum arc.

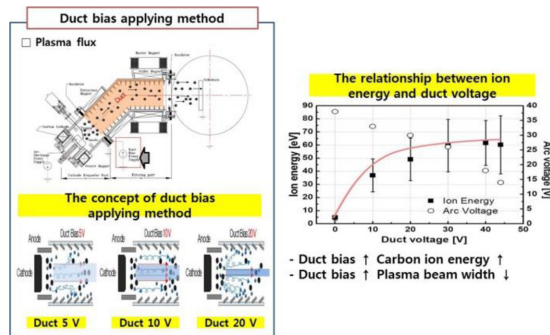


Fig. 2. Concept of duct bias in FCVA system.

cess to provide optimum conditions for deposition.

The initial optimal pressure for the deposition process was 5×10^{-3} Pa. During ta-C coating, four processes including (1) etching, (2) etching with sputtering, (3) sputtering with ta-C, and (4) ta-C coating were performed.

2-2. Tribological Analysis

The friction and wear properties are determined using a ball-on-disk type of tribo-meter. The balls (diameter = 6 mm, WC, SUJ2, SUS304, and Al_2O_3) are positioned against the disk, which is located 3 mm eccentrically from the center of the coated disc.

A 10 N normal load is then used to push the ball downward while the disc rotates at 200 rpm through 10,000 cycles, which constitutes a sliding distance of 376 m.

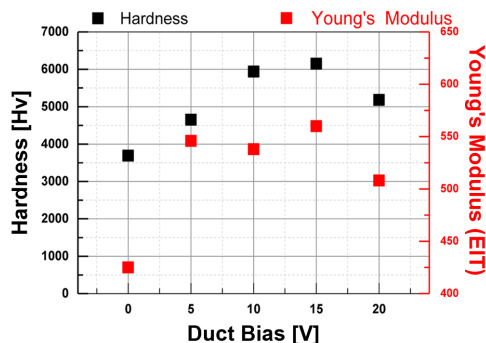


Fig. 3. Mechanical properties (hardness and Young's modulus of ta-C coating as a function of duct bias.

The images of the worn surfaces were investigated by optical microscopy. Meanwhile, a surface profiler was also used to measure the ta-C coating thickness and wear rate after tribo-coupling [3].

3. Results and Discussion

3-1. Mechanical properties of ta-C coating as a function of duct bias voltage

Fig. 3 shows the mechanical properties of the ta-C coating as a function of duct bias. The hardness and Young's modulus of ta-C coatings are dependent on the duct bias voltage up to 15 V. This directly correlates with the sp^3 ratio in the coated film.

However, the mechanical properties decrease with increasing duct bias (up to 20 V). This might be attributed to the surface temperature induced by the high plasma density. McKenzie also reported a similar relationship between mechanical properties and ion energy distribution [4].

Because the hardness value is attributed to the concentration of C-C sp^3 bonds in a component, it can be deduced that the deposition of the ta-C film with 15 V duct bias produces a coating with the highest sp^3 ratio.

The average coating thickness and average wear depth of the ta-C-coated samples are tabulated in Table 1 as a function of duct bias. From Table 1, for the tribo-test with the WC ball, average wear

Table 1. Thickness and wear depth after tribo-tests

Duct Bias (V)	ta-C Thickness (nm)	Average Wear Rate ($10^{-6} \times \text{mm}^3$)			
		SUJ2	WC	SUS304	Al_2O_3
0	600	1.524	9.463	0.987	3.257
5	700	0.113	12.112	1.081	3.577
10	800	2.469	19.706	1.812	2.861
15	800	1.355	14.801	2.123	6.616
20	800	0.171	22.719	0.625	1.579

Table 2. Mean contact pressure for ta-C coating tribo-couples with different counterparts

Counterparts	Mean Contact Pressure, P_m (GPa)
SUJ2	0.95
WC	1.3
SUS304	0.95
Al_2O_3	1.1

depths on ta-C coated surfaces are higher than their average coating thicknesses. As wear depths are greater than ta-C film thicknesses, the WC ball has penetrated the coating and has caused delamination on the substrate surface.

However, the same phenomenon is not apparent for the interaction with SUJ2, SUS304, or Al_2O_3 , where average wear depths are smaller than the ta-C coating thicknesses. Therefore, tribo-coupling only affects the surface coating without penetrating into the substrate layer for these counterpart materials.

3-2. Mean contact pressure

In order to analyze the reason for the asperity of the wear track in the ta-C-WC tribo-coupling, Hertz's Theory is applied to calculate the mean contact pressure, P_m of each tribo-pair [5].

Calculated values of P_m are tabulated in Table 2. Results from Table 2 reveal that the ta-C coating with the WC ball yields 1.3 GPa of P_m , which is the highest among the four types of counterpart materials used in this project. Meanwhile, the P_m of ta-C with the other three types of counterparts, namely SUJ2, SUS304, and Al_2O_3 , shows compara-

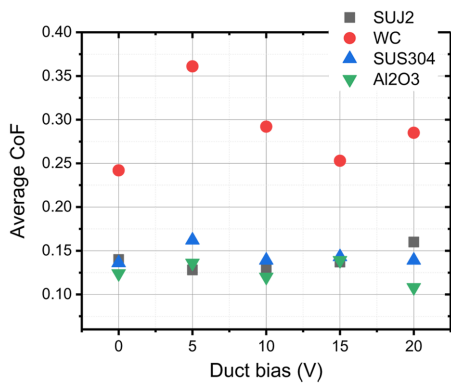


Fig. 4. Frictional behavior of ta-C coated samples with various ball materials.

tively low values compared to WC.

From the calculations, the mean contact pressure exerted between the WC and ta-C tribo-couple is higher than in the other ball materials.

The reason for this is that the dimensions of the Hertzian contact area are determined by geometrical and mechanical factors, and especially by the Young's modulus.

The Young's modulus for each ball material is;

WC (650 GPa), Al₂O₃ (300 GPa), SUS304 (200 GPa), and SUJ2 (200 GPa). Thus, the relatively high value of wear rate of the ta-C/WC tribo-couple and the rough surface and asperity of the wear track shown in Section 3.4 can be explained.

3-3. Frictional behavior as a function of duct bias

Fig. 4 shows the average coefficient of friction (CoF) of samples deposited under different duct bias after tribo-tests for various ball materials. From the data obtained, tribo-coupling of the ta-C coating with SUJ2, SUS304, and Al₂O₃ ball surfaces generally exhibits low CoF, in the range of 0.108 to 0.160.

Among these three tribo-pairs, ta-C/SUS304 generates a slightly higher friction coefficient overall. However, friction values of the ta-C surface show only slight differences among the three types of counterpart materials.

On the other hand, the friction behavior of ta-C

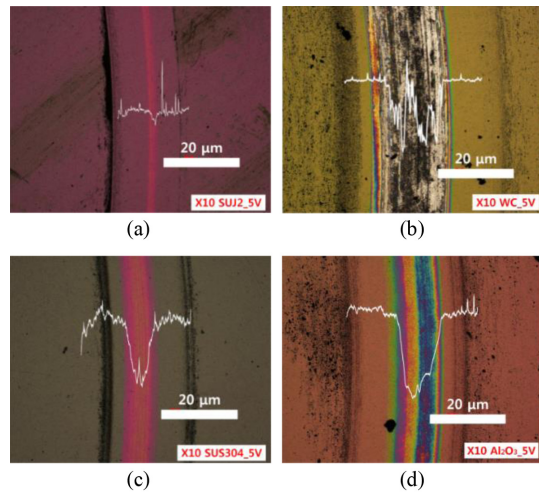


Fig. 5. Wear images for ta-C (5 V duct bias) tribo-couple with (a) SUJ2, (b) WC, (c) SUS304, and (d) Al₂O₃ balls.

and WC deviates from that of the other three counterpart materials. It exhibits a comparatively higher friction value, between 0.242 and 0.361. Thus, it is obvious that the counter-body material influences the friction behavior of the ta-C coating.

This is proven by SUJ2, which shows the best frictional behavior with ta-C coatings among all materials, whereas the ta-C/WC tribo-couple is less suitable for enhancing tribological characteristics owing to its higher friction value.

3-4. Surface morphology and wear track analysis

In terms of the wear parameter, the interaction of ta-C with a WC ball is remarkably high, whereas it is lowest with the SUJ2 ball. Fig. 5 shows the worn area of samples obtained from ball-on-disc tribo-tests.

In Fig. 5, significant differences among wear images for ta-C coatings (deposited under 5 V duct bias) tested using SUJ2, WC, SUS304, and WC balls are notable. For ta-C with a WC ball contact, the wear track is rough and asperity is observed. The wear track is relatively wider compared to SUJ2, SUS304, and Al₂O₃.

Shiny compositions are noticeable on the wear track for the ta-C/WC interaction. Yu et al. have proven that

fatigue cracks will readily propagate down to the interface with the aid of interfacial stresses, which will cause the local delamination of the coating [6].

At this point, the coating has failed catastrophically. Meanwhile, with SUJ2, SUS304, and Al_2O_3 as counter materials, wear tracks on the ta-C surface are smooth. Tribo-coupling causes only light effects on the sample surfaces, with rainbow colors differing significantly from those in the WC ball interaction, which shows a dark color instead.

Often, the friction and wear behaviors of contacting surfaces are controlled by the formation of transfer layers on sample surfaces. A transfer layer is generated when two bodies consisting of hard and soft materials undergo tribo-coupling. This layer is formed through mechanical mixing of the two materials. The initial formation of a transfer film is associated with significant wear of the coated surface. Consequently, once the transfer film is formed, the wear rate reduces to a low steady state value. This initial running-in wear is essential to ensure low friction and wear over long periods and is often observed with DLC coatings [7].

By analyzing the images captured by optical microscopy, it can be deduced that the best transfer layer is generated on the ta-C/SUJ2 tribo-couple, which leads to its low wear rate behavior. The worst transfer layer is generated on the ta-C/ Al_2O_3 tribo-couple, causing it to exhibit a higher wear rate. However, the tribo-couple with the WC ball could not be analyzed in terms of transfer layer owing to the penetration into the substrate surface. Generation of high carbon content on the transfer layer after tribo-coupling results in a low friction coefficient and wear rate [8-14].

From Fig. 6, it can be observed that for tribocoupling with ta-C deposited under 10 V and 15 V, the duct bias generally yields a higher wear rate for the four types of counterpart materials. This phenomenon can be observed with SUS304 and Al_2O_3 , which achieve their highest wear rate at 15 V, whereas SUJ2 and WC achieve their highest wear rate at 10 V.

From the mechanical property evaluations, ta-C

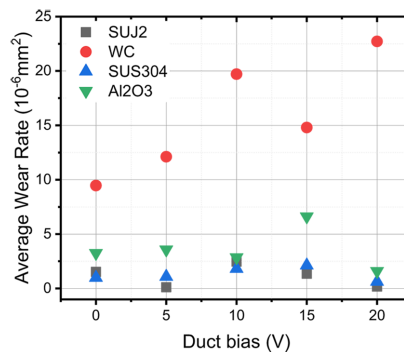


Fig. 6. Wear behavior of ta-C coated samples with various ball materials

coatings at 10 V and 15 V are ranked as the top two in terms of hardness and Young's modulus. Moreover, the coating thickness of ta-C is also the highest for deposition under 10 V and 15 V, as already discussed.

It is normal that the tribological performances of a substance are often influenced by its mechanical properties. Thus, a bold inference can be made in which the wear rate of a tribo-system increases with increasing hardness of its surface coating for the case of ta-C. In this context, focus is on hardness of the ta-C surface itself, without considering the mechanical properties of counterpart materials.

It was proven by Wang et al. that a harder combination of tetrahedral amorphous carbon (ta-C) coating with counterpart materials will result in a higher wear rate of the ta-C coating in ambient air [9].

Nevertheless, the hypothesis that the wear rate of ta-C increases with increasing surface hardness can only be verified based on results obtained from experimental work. So far, no study results have been found to support this hypothesis. Thus, it is suggested that future work can be performed to study the influence of coating hardness on the wear rate of tribo-systems.

4. Conclusions

The friction and wear properties of ta-C coatings

sliding against four types of balls in air have been investigated by using a ball-on-disk tribo-meter at 10 N. The conclusions of the study are as follows:

The hardness and Young's modulus of ta-C coatings are dependent on the duct bias voltage up to 15 V. This is directly correlated with the sp^3 ratio in the coated film. However, the mechanical properties decrease with increasing duct bias up to 20 V. This might be attributed to the surface temperature induced by the high plasma density during coating.

For ta-C coatings sliding against WC balls, the CoF and wear depth were higher than for other counterpart material balls: SUJ2, SUS304, and Al_2O_3 .

The high Young's modulus of WC material (650 GPa) may be attributed to a larger contact area resulting from the mean contact pressure.

For ta-C coatings sliding against SUJ2 balls, the CoF varies from 0.128 to 0.160 up to a 20 V duct bias. When we consider the contact pressure and Young's modulus of SUJ2, this counterpart material has a significant effect regarding friction and wear reduction.

In order to reduce friction and wear, not only the mechanical properties of the ta-C coating should be increased, but the physical properties of the counterpart material are also very important for tribological applications.

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