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**Paper:**

# New Droplet Removal Polishing Method for Diamond-Like Carbon with Carbon Fiber Brush

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**In this paper, we propose a new polishing method for diamond-like carbon (DLC) coatings using a carbon fiber brush (CFB). Surface finishing is an important process for DLC coating applications. A lapping process is widely used for attaining tetrahedral amorphous carbon (ta-C) coatings, which are a type of DLC coating containing many droplets, to obtain fine flat surfaces. The lapping process removes protuberant parts of droplets rather than the entire droplet. In this paper, we propose a new polish brush material made of carbon fiber, called CFB. Carbon fiber has both mechanical strength due to its hard carbonaceous material and flexibility due to its fiber structure. In polishing tests, CFB removed droplets from ta-C coatings and the removal effect increased with the shortening of the brush length. The surface profiles of the polished surfaces indicated that a shorter brush length yielded deep scratch marks on ta-C surfaces. Consequently, the arithmetic average surface roughness of the polished ta-C surfaces, $S_a$, had almost the same value as that of a non-polished surface. Here, we show the ability of CFB to remove the droplets without an increase in the surface roughness. The CFB with the longest brush length in the present study (12 mm) showed a ten-point average roughness $S_{ZJIS} = 75$ nm and $S_a = 4.7$ nm, which were 59% and 22% lower than those of the non-polished surface, respectively. Furthermore, the longest CFB removed the entire droplets whereas a shorter CFB merely removed the protuberant part of the droplets. The result indicates that CFB polishing can remove entire droplets, which result in abrasive wear or deterioration. From other polishing tests, the optimum polishing distance was determined. Shorter polishing distances could not remove droplets sufficiently whereas longer polishing distances caused deep scratches on ta-C surfaces due to the material transferred to the CFB. Accordingly, the polishing distance of 600 m showed the best surface finishing with $S_{ZJIN} = 25$ nm and $R_a = 0.43$ nm, which were 86% lower than and similar to those of the non-polished ta-C surface, respectively.**

**Keywords:** carbon fiber brush, diamond-like carbon, polishing, droplet, tetrahedral amorphous carbon

## 1. Introduction

Recently diamond-like carbon (DLC) coatings have attracted increasing attention as a coating material. DLC coatings, which have a combined structure of $sp^2$ bond and $sp^3$ bond, are one type of amorphous carbonaceous coatings. They have several excellent properties such as high hardness, low frictional coefficient, high wear resistance, and chemical stability [1–3]. Thus, they have been increasingly applied to cutting tools, engine components, etc. [4–8].

Among DLC coatings, extremely hard coatings containing no hydrogen are called tetrahedral amorphous carbon (ta-C) coatings. They are highly promising materials for friction applications owing to their excellent mechanical properties [9]. The ta-C coatings deposited via physical vapor deposition are generally known to have some particle residues, called droplets, on their surfaces, which are formed with a nucleus of fine particles detached from the carbon target at the time of their deposition [10]. Numerous droplets are formed in ta-C coatings deposited via vacuum arc vapor deposition, a method well known for attaining good-quality ta-C coatings. The vacuum arc vapor deposition method can deposit fine coatings by using high-energy ions discharged from the cathode spot to be formed on the cathode surface, but it discharges a large quantity of droplets simultaneously [11]. Any droplets present on a DLC coating will create a protuberant part on its surface to deprive it of smoothness. In addition, such droplets on DLC coatings could reportedly cause their abrasive wear [12] and trigger their thermal degradation in high-temperature environments [13].

Recently, a new method called filtered cathodic vacuum arc (FCVA) deposition has been developed to reduce the droplets formed while depositing coatings [14–18]. The physical vapor deposition method using arc discharge can deposit hard and high-density DLC coatings by efficiently ionizing carbon atoms through its high-energy arc discharge. However, arc discharge generates sub-micron- to several-micron-sized carbon fine particles, resulting in droplets, which will degrade the smoothness of DLC coatings. In contrast, in the FCVA method, a path of the ionized carbon is bent by the electromagnetic field, resulting in the prevention of unionized carbon fine particles from reaching a substrate. However, unlike liquid droplets from a metal cathode, carbon fine particles are a solid material [19] and they do not stick quickly to the chamber's inner wall, making it difficult to remove droplets completely even using FCVA [20]. Hence, there is a need to develop a technology for removing droplets formed during coating depositions.

As machine parts are generally subjected to polishing processes to improve their surface profiles [21–24], DLC products also generally undergo a surface smoothing process to prevent their friction and wear properties from declining due to the presence of any droplets. The most widely applied method for removing droplets currently is a lapping process [11, 12]. In the lapping process, the protuberant part of droplets is removed to improve the surface roughness significantly. However, the part of the droplets below the surface is not removed. Such residual parts of droplets could cause adverse effects such as cracks/peeled-offs or accelerated wear in the same way as in ordinary droplets [25]. Hence, there is a need to develop a new method for removing entire droplets.

In this study, we develop a new method for removing droplets from ta-C coatings with a carbon fiber brush (CFB) made of bound carbon fibers. Carbon fibers, a fibrous material of approximately 7 $\mu$m in diameter, have such mechanical properties as excellent strength and elastic modulus. As they also have excellent self-lubricity [26], new friction materials are being developed by binding carbon fibers in a loop shape to reduce starting torques [27]. In that study about the looped CFB, authors consider that the flexibly self-deformable brush shape causes the unique friction property reducing starting torques.

Owing to their flexibility and multiple contacting points, brush materials have been industrially used to remove particles without damaging the surface [28]. However, because of the relatively hard droplets present on DLC coatings, no successful lapping examples using conventional brushes have been reported. In this study, we have conducted experiments using a CFB having the combined properties of a flexibly deformable brush and a hard carbon fiber to develop a new lapping method that attains excellent removal of droplets on ta-C coatings and is low in aggressiveness to the opposite face.

In this study, we reveal the basic properties of lapping ta-C coatings with a CFB, which is a highly promising lapping brush material, and discuss their lapping mechanism.

## 2. Experimental Method

### 2.1. Carbon Fiber Brush and ta-C Specimens

In this study, CFB specimens are manufactured from carbon fibers TOREKA TC-700SC-12000 made by Toray Industries Inc. First, approximately 420,000 carbon fibers of diameter 7 $\mu$m are bound and are fixed in a thermal contraction tube to prepare a cylindrical brush of diameter 6.0 mm. Then, the cylindrical brush is inserted into

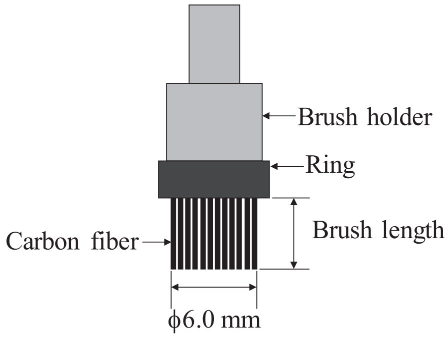



**Fig. 1.** Schematic of CFB specimen.

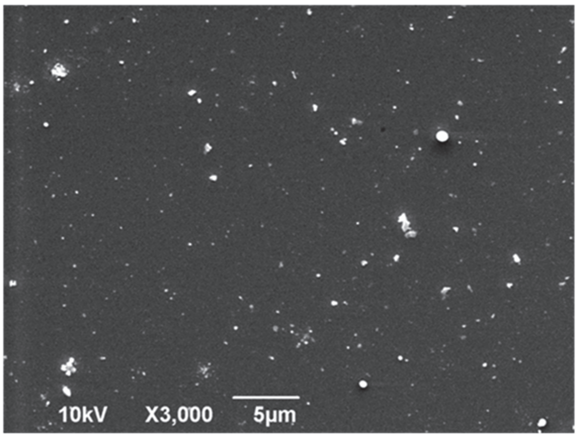



**Fig. 2.** SEM image of as-deposited ta-C surface.

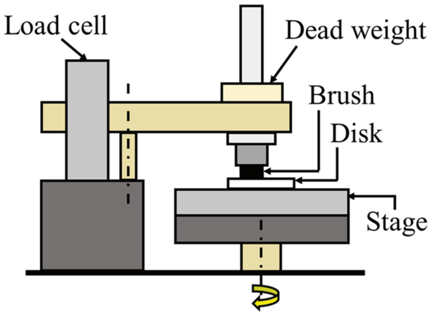
a cylindrical holder and tightened with a tightening ring to complete the CFB (**Fig. 1**). Three kinds of CFBs are manufactured with different brush lengths, 1.5, 3.0, and 6.0 mm, and the effects of the brush length on the lapping performance are verified.

A ta-C coating, which is to be lapped, is deposited on a silicon wafer via the FCVA method. **Fig. 2** shows a scanning electron microscopy (SEM) image of the ta-C coating used in this study. From this figure, we can observe the white images of droplets scattered on the surface. In this study, lapping experiments are conducted with a ta-C coating having hardness of 38.3 GPa and arithmetic average surface roughness of $S_a = 6.1$ nm.

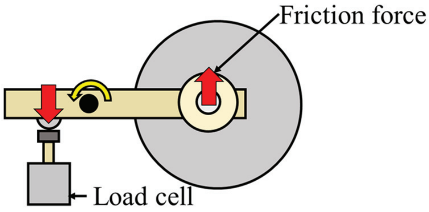
### 2.2. Lapping Equipment

In this study, the lapping equipment shown in **Fig. 3** is used, where a CFB specimen is installed at the swing arm tip via a jig and vertical load is applied by the dead weight of 1.0 N installed on the axis of the CFB. Lapping is performed by the relative motion to be generated between the CFB and the disk specimen by rotating the rotary stage to which the ta-C disk specimen is attached.

The lapping experiments are undertaken in the atmosphere. The experiments are conducted in the following conditions: lapping rate, 200 mm/s; vertical load, 1.0 N; lapping distance, 200 m. Three different lengths of CFB specimens, 1.5, 3.0, and 6.0 mm, are prepared to




(a) Side view




(b) Overview

**Fig. 3.** Schematics of pin-on-disk type polishing equipment.

check the effects of the brush length on the lapping quality of the ta-C coating. Experiments with a CFB of brush length 6.0 mm are conducted by varying the lapping distance from 200 to 400, 600, 800, and 1000 m to check the effects of the lapping distance on the lapping quality.

### 2.3. Surface Observations with SEM and AFM

In this study, the surface profiles of the ta-C coating are observed with atomic force microscopy (AFM) and SEM before and after the lapping experiments. AFM can observe the surface irregularities with resolutions of the order of nanometers by scanning the specimen's surface with a probe fitted at the cantilever tip. SEM can observe the surface profiles by detecting the secondary electrons to be generated by exciting the electrons in the specimen material by scanning the specimen surface with the electron beam emitted from an electron gun. In this study, AFM is used to acquire the height-directional distributions of the surface before and after lapping, and SEM is used to observe the surface profiles in a wider vision before and after lapping.

The ten-point average surface roughness, $S_{ZJIS}$, acquired from the AFM images is used to evaluate the removal of droplets. The heights of some large droplets are sub-micron level. In this study, an extremely smooth ta-C coating having an arithmetic average surface roughness $S_a = 6.1$ nm is used. Hence, we may consider that the ten-point average surface roughness is influenced only by the droplet heights: an important indicator to evaluate the droplet removal properties of CFB in this study. From the AFM images, the arithmetic average roughness $R_a$ for the cross section with no droplets is calculated to evaluate the lapping properties of CFB in lapping the ta-C coating itself. For calculating the surface roughness, a cut-off value of 3.3 $\mu$m and an evaluation length of 17 $\mu$m are used.

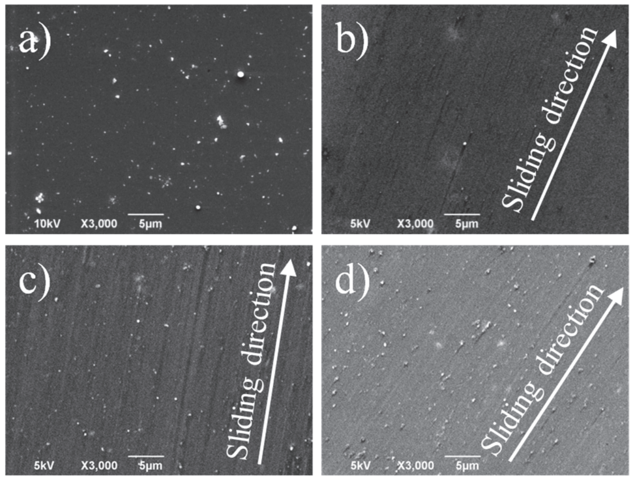



**Fig. 4.** SEM images of ta-C surfaces (a) before polishing, and after polishing with the brush lengths of (b) 1.5 mm, (c) 3.0 mm, and (d) 6.0 mm.

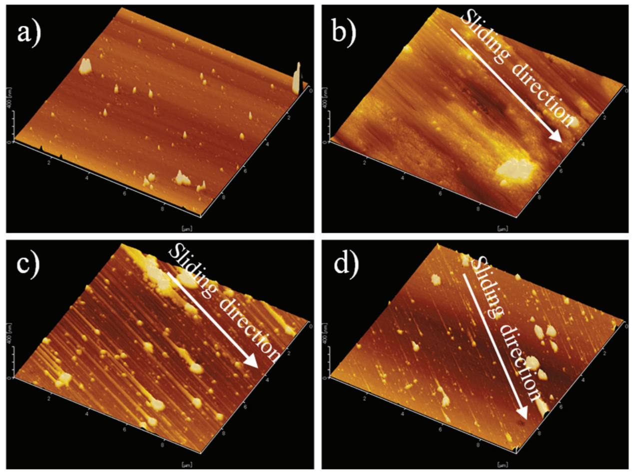



**Fig. 5.** AFM images of ta-C surfaces (a) before polishing, and after polishing with the brush lengths of (b) 1.5 mm, (c) 3.0 mm, and (d) 6.0 mm.

## 3. Experimental Results

### 3.1. Effects of Brush Length on Lapped Surface

**Figures 4–6** show the SEM images of the ta-C surface, the AFM images of the ta-C surface, and the cross-sectional profiles of the droplet-less area, respectively, before and after lapping with CFBs of different brush lengths. We can observe from **Fig. 4** that the droplets present before lapping have been mostly removed by lapping with a CFB of brush length 1.5 mm and that a certain quantity of droplets has been removed by lapping with CFBs of brush lengths 3.0 mm and 6.0 mm. A comparison between **Figs. 4(c)** and **(d)** reveals that lapping with a CFB of brush length 3.0 mm removes more droplets than that with a CFB of brush length 6.0 mm. Thus, CFB of a shorter brush length can remove more droplets than that of a longer brush length. As several post-lapping residual droplets are relatively small in diameter, the removal

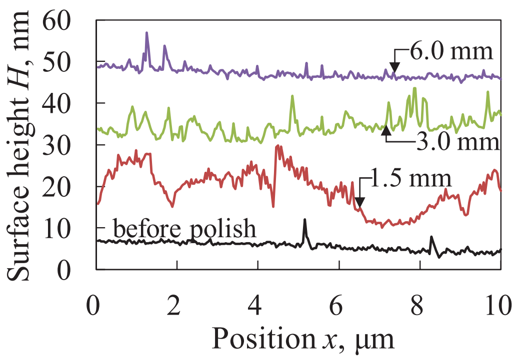



**Fig. 6.** Cross-sectional profiles of the droplet-less area before polishing, and after polishing with the brush lengths of 1.5 mm, 3.0 mm, and 6.0 mm.

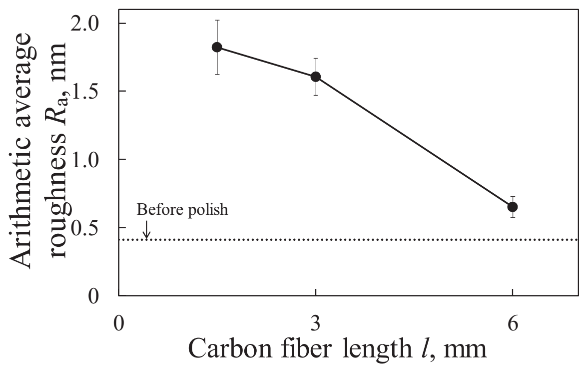



**Fig. 8.** Effect of brush length on the arithmetic average roughness of droplet-less area.

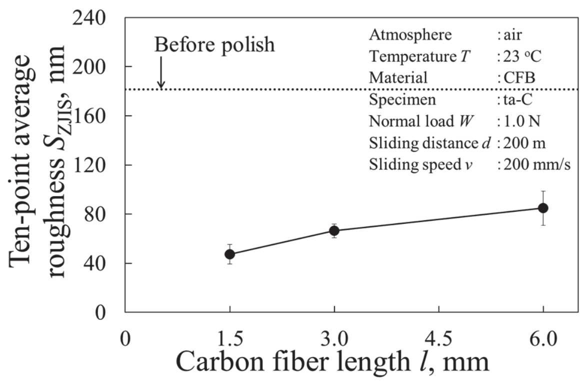



**Fig. 7.** Effect of brush length on the ten-point average surface roughness.

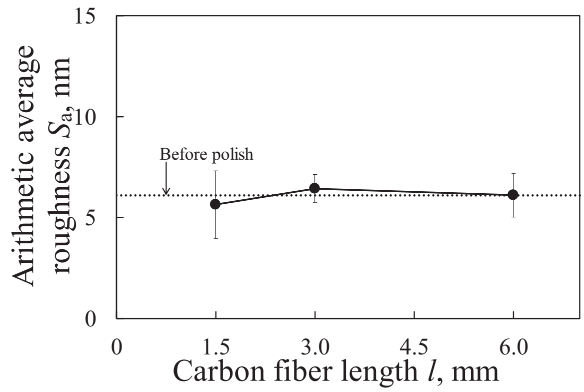



**Fig. 9.** Effect of brush length on the arithmetic average surface roughness of the entire ta-C surface area.

of large droplets present on the surface before lapping has been prioritized. The droplet-less area, very smooth ($R_a = 0.33$ nm) before lapping, has been observed to have some lapping scratches after lapping with CFBs.

**Figure 7** shows the ten-point average surface roughness $S_{ZJIS}$ before and after lapping with CFBs of different brush lengths as calculated from the AFM images in **Fig. 5**. The ten-point average surface roughness of the ta-C coating, which was 181 nm before lapping, is reduced to 47, 66, and 85 nm after lapping with CFBs of brush lengths 1.5, 3.0, and 6.0 mm, respectively. They represent reductions of 74%, 63%, and 53%, respectively, from the value before lapping. Thus, the shorter brush lengths of CFBs have evidently reduced the ten-point average surface roughness.

**Figure 8** shows the arithmetic average roughness $R_a$ as calculated from the cross-sectional profiles of the droplet-less area in **Fig. 6**. From the figure, we can observe that the arithmetic average roughness of the ta-C coating, which was 0.41 nm before lapping, is increased to 1.8, 1.6, and 0.65 nm after lapping with CFBs of brush lengths 1.5, 3.0, and 6.0 mm, respectively. They represent increases of 350%, 290%, and 60%, over the value before lapping, respectively. Thus, the shorter brush lengths of CFBs have evidently increased the arithmetic average roughness of the droplet-less area.

The AFM images in **Fig. 5** show the droplets scattered on the flat surface as demonstrated by their peak heights. Therefore, any removal of such droplets from the surface should lead to a reduction of the ten-point average surface roughness. While **Fig. 7** shows that CFBs of shorter brush lengths can more efficiently remove droplets, they also evidently degrade the surface profiles more as shown by the cross-sectional profiles in **Fig. 6** and the arithmetic average roughness in **Fig. 8**.

**Figure 9** shows that lapping with CFBs of different brush lengths has no effect on the arithmetic average surface roughness of the entire ta-C surface area. That is, lapping with a CFB of brush length 6 mm has generated the same arithmetic average surface roughness as that before lapping, probably because the smoothing effects of removing the droplets and the effects of generating lapping scratches have cancelled out each other. In other words, the experiments have proved that lapping with a CFB can remove droplets and can achieve a degree of arithmetic average surface roughness similar to that of the deposited coating.

### 3.2. Effects of Lapping Time on Lapped Surface

**Figures 10** and **11** show the SEM and AFM images, respectively, of the ta-C coating surface before and after lapping for the lapping distances of 200, 400, 600, 800,

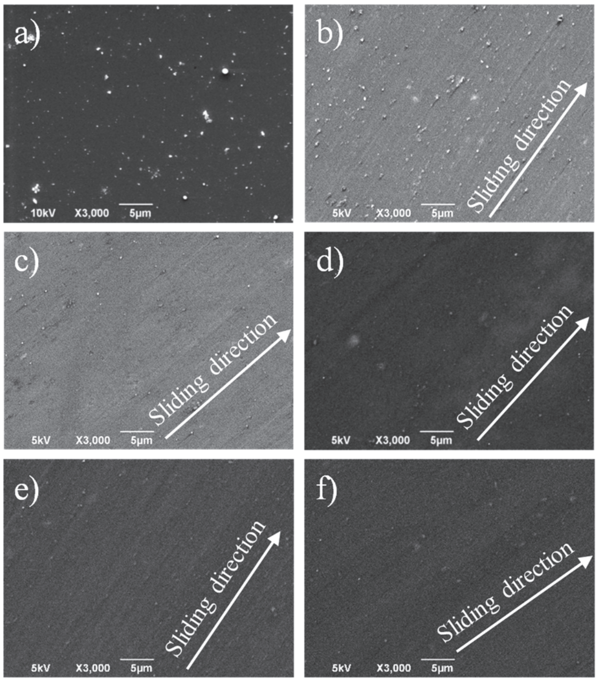



**Fig. 10.** SEM images of ta-C (a) before polishing, and after polishing using CFB with the polishing distances of (b) 200 m, (c) 400 m, (d) 600 m, (e) 800 m, and (f) 1000 m.

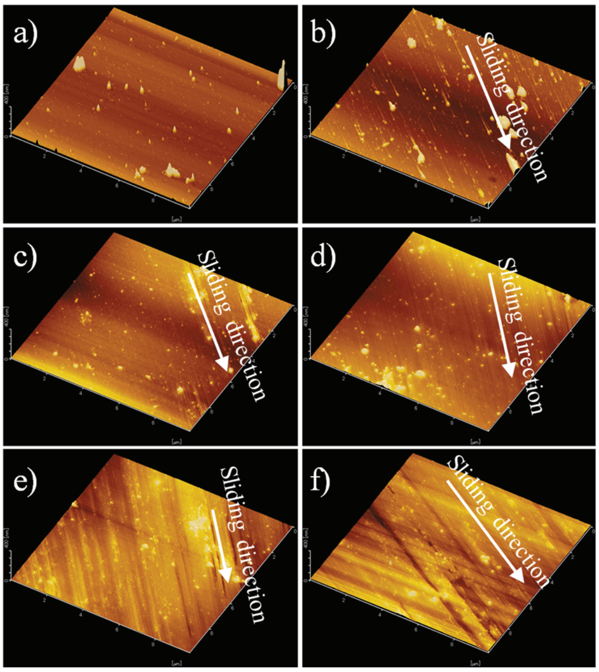



**Fig. 11.** AFM images of ta-C (a) before polishing, and after polishing using CFB with the polishing distances of (b) 200 m, (c) 400 m, (d) 600 m, (e) 800 m, and (f) 1000 m.

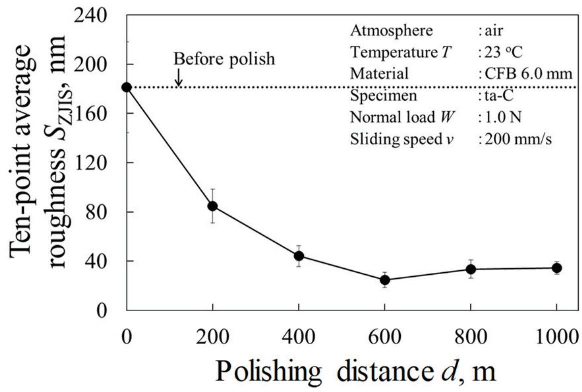



**Fig. 12.** Effect of polishing distance on the ten-point average surface roughness.

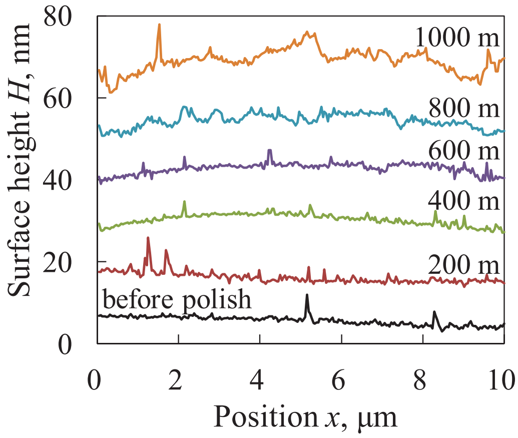



**Fig. 13.** Cross-sectional profiles of droplet-less area before polishing, and after polishing using CFB with the polishing distances of 200 m, 400 m, 600 m, 800 m, and 1000 m.

and 1000 m. A CFB of brush length 6 mm is used for these lapping experiments. We can observe from **Fig. 10** that lapping with a CFB has evidently removed droplets from the ta-C coating surface. While lapping for the lapping distance of 200 m has left relatively small droplets unremoved, such residual droplets decrease in quantity in accordance with the lapping distances.

The ten-point average surface roughness is calculated as shown in **Fig. 12** based on the AFM measurement results in **Fig. 11**. The ten-point average surface roughness before lapping is 181 nm, whereas that for the lapping distances of 200, 400, 600, 800, and 1000 m is reduced to 85, 44, 25, 33, and 34 nm, respectively. That is, compared with the ten-point average surface roughness before lapping, it is decreased by 53%, 76%, 86%, 82%, and 81%, respectively. The ten-point average surface roughness has a tendency to decrease for the lapping distances up to 600 m but it stagnates for longer lapping distances.

**Figure 13** shows the cross-sectional profiles of the droplet-less areas in **Fig. 11**, and **Fig. 14** shows their arithmetic average roughness. The arithmetic average roughness before lapping is 0.41 nm, whereas it is increased to 0.65, 0.49, 0.43, 0.88, and 1.2 nm, after lapping for the lapping distances of 200, 400, 600, 800, and 1000 m, respectively. That is, compared with the arithmetic average roughness before lapping, it is increased by 59%, 19%, 5.7%, 120%, and 200%, respectively. The arithmetic av-

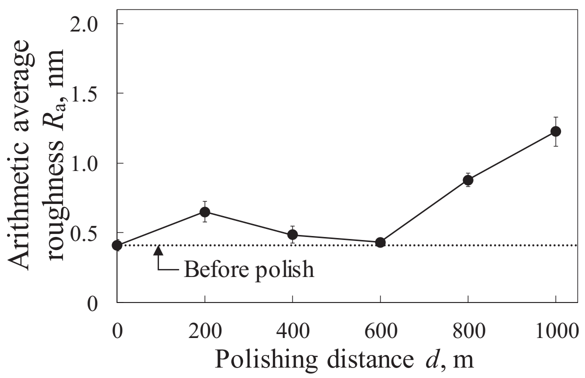



**Fig. 14.** Effect of polishing distance on the arithmetic roughness of droplet-less area.

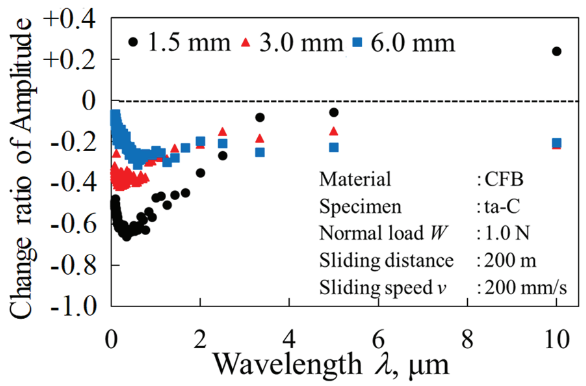



**Fig. 15.** Fast Fourier transform result of the polished surface. Each value of the polished surface is divided by the value of the non-polished surface at the same wavelength.

erage roughness remains approximately the same as that before lapping for the lapping distances up to 600 m but it has a tendency to increase for longer lapping distances.

The aforementioned experimental results reveal that, in lapping with a CFB, the lapping distance is an important factor having a significant influence on the lapped surface profiles. As the lapping process generally depends heavily on the maximum surface pressure of a lapped surface, the efficiency of the lapping process decreases as the lapping time increases, because the entire processed surface is so smoothed as to have no local high surface pressure areas that it is not further lapped. Therefore, except for industrial productivity and field sags, generally, there are no special disadvantages in making the lapping time longer. However, in this study, lapping for the lapping distances of longer than 600 m has degraded the surface profiles and arithmetic average roughness as the lapping distance increases as shown in **Figs. 13** and **14**. These experimental results suggest that the mechanism of lapping with CFB should be different from that of lapping with conventional DLC coatings.

## 4. Discussions

### 4.1. Mechanism of Lapping with CFB

The surface profiles of the ta-C coatings are analyzed before and after lapping with CFBs of brush lengths 1.5, 3.0, and 6.0 mm to reveal the effects of the brush length of the CFB on the lapping properties of ta-C coatings. In the spectral analyses, each line among 256 lines of the AFM images in **Figs. 5** and **11**, which are composed of 256 $\times$ 256 numerical values, is Fourier transformed [29]. The amplitude change ratio is calculated by dividing the amplitude value of each wavelength by its value before lapping as shown in **Fig. 15**, where any larger negative amplitude change ratio values are considered to indicate that the surface has been made smoother.

We can observe from **Fig. 15** that, in the wavelength range between 0 and 2 $\mu$m, shorter brush lengths result in larger negative amplitude change ratio values. In other words, given that the droplets present on the ta-C surface in the lapping experiments are between sub-microns and several microns in size, **Fig. 15** proves that shorter brush lengths remove more droplets. This corresponds with the measurement results of the ten-point average surface roughness in **Fig. 7**, which indicate that shorter brush lengths result in smaller ten-point average surface roughness values. With one piece of fiber taken for a beam, when the same force vertically acts on the fiber, a shorter fiber will become less bent, so that a shorter brush length makes it stiffer, with a resultant increase in the load that acts on the droplets.

In the wavelength range between 3 and 5 $\mu$m, the CFB of brush length 1.5 mm produces a smaller amplitude change ratio than the CFBs of longer brush lengths. In addition, it produces an amplitude change ratio of $+0.2$ or more with the wavelength of 10 $\mu$m. That is, lapping with a CFB of brush length 1.5 mm raises the amplitude of frequency components between 6 and 10 $\mu$m. **Fig. 8** shows that the arithmetic average roughness of the droplet-less area increases with a decrease in the brush length. That is, lapping with a CFB of a shorter brush length removes more droplets but its high stiffness generates some lapping scratches on the ta-C coating. The carbon fibers used in this study have a diameter of 7 $\mu$m. **Fig. 15** shows positive amplitude change ratio values in the wavelength range of 6 to 10 $\mu$m, which is almost same value of the fiber diameter, indicating that CFBs of shorter brush lengths have such higher stiffness as to make the fibers themselves a cutting edge to micro-cut the ta-C surface (**Fig. 16(a)**).

As carbon fibers are fine fibers, it is difficult to measure their hardness. However, during the processing of composite materials containing these fibers, they are known to wear diamond and DLC-coatings heavily [30–32]. Carbon fibers are also reported to have the same Young's modulus as DLC coatings [33]. Therefore, in this study, we consider that the ta-C coating has been worn by sliding with the carbon fiber edge. The droplets, which are amorphous carbons containing many $sp^2$ bonds, are considered softer than ta-C coatings [9, 11].

As compared with the brush length of 1.5 mm, the

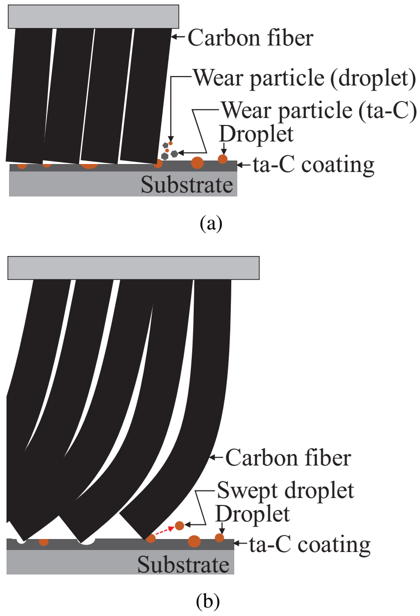



**Fig. 16.** Polish mechanism of CFB with (a) short brush length and (b) long brush length.

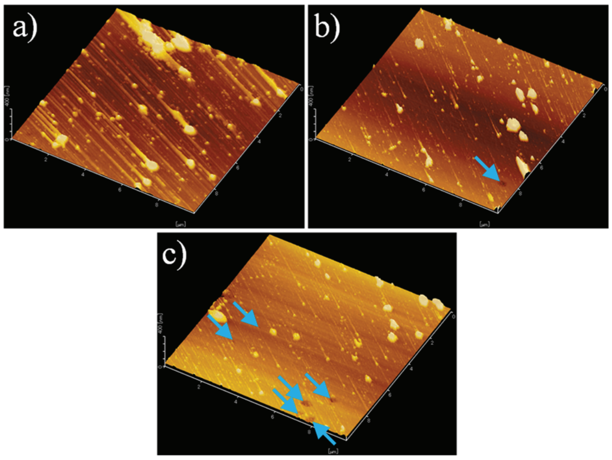



**Fig. 17.** Droplet sweeping ability with long CFB. (a) No droplet was swept away with CFB of brush length 3.0 mm, (b) a droplet was swept away with CFB of brush length 6.0 mm, and (c) the longest CFB with the brush length of 12 mm swept away more droplets.

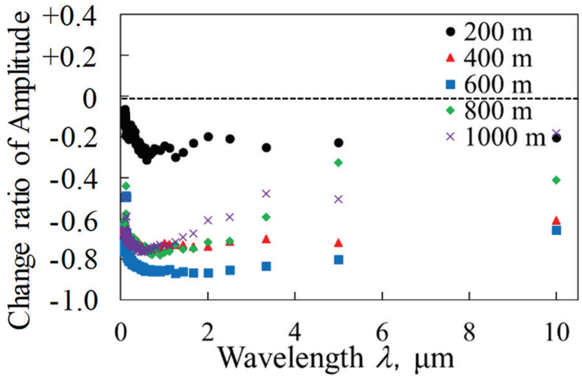



**Fig. 18.** Fast Fourier transform result of polished surface for different polishing distances. Each value of polished surface is divided by the value of the non-polished surface at the same wavelength.

brush length of 6.0 mm exhibits a relatively small stiffness and can flexibly deform, so that it can buckle relatively so largely that it can behave less as a cutting edge. The amplitude change ratio in the wavelength range between 6 and 10 $\mu$m appears to have taken a negative value for these reasons. The brush length of 6.0 mm, despite having a lower droplet removal effect than shorter brush lengths, removes some droplets to contribute to the amplitude reduction in the low-wavelength range.

In view of the aforementioned discussions, using a CFB of a longer brush length is considered appropriate to realize an excellent lapping process. Accordingly, a CFB of brush length 12 mm is newly manufactured and lapping experiments are conducted with it to obtain the ten-point average surface roughness $S_{ZJIS} = 75$ nm and the arithmetic average surface roughness $S_a = 4.7$ nm, which represent reductions of 59% and 22%, respectively, as compared with those before lapping. These results demonstrate excellent lapping properties. The arithmetic average roughness of the droplet-less area $R_a = 0.70$ nm is increased by approximately 0.3 nm as compared with that before lapping (0.41 nm). However, the droplet-less area after lapping has a high level of smoothness with $R_a = 1.0$ nm or less. From the AFM images, we can observe several spots after lapping where the droplets have been removed (**Fig. 17**). They are not observed from the AFM images after lapping with CFBs of brush lengths up to 3.0 mm. Lapping with CFBs of short brush lengths with high stiffness appears to have merely removed the protuberant part of the droplets in the same way as the conventional lapping methods.

It is experimentally established that the interface between the droplets and DLC coating contains more $sp^2$ bonds than bulk part [12] and that the presence of such weakly bonded layers triggers the detachment of the droplets [11]. The use of CFBs of longer brush lengths bends the fibers due to their flexibility and sweeps out the entire droplets without breaking them up (**Fig. 16(b)**).

This study revealed that the use of long brushes is essential for developing CFBs that are low in opponent aggressiveness and excellent in the ability to sweep out droplets. However, as any increase in the brush length could decrease the droplets removal effect, it would also be important to design an optimum brush length that would match the ta-C to be lapped.

### 4.2. Accumulation of Lapping Debris

The surface of the ta-C coating is spectrally analyzed before and after lapping with a CFB of brush length 6.0 mm for the distances between 200 and 1000 m to reveal the effects of the lapping distances on the surface profiles of the ta-C coating. **Fig. 18** shows the spectral analysis results, which indicate that, in the lapping

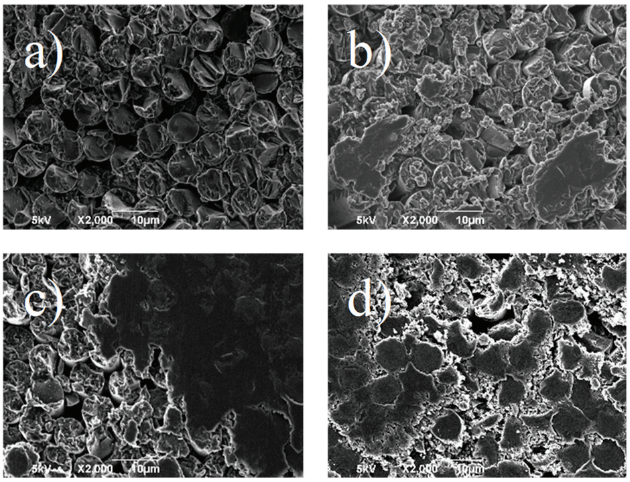



**Fig. 19.** SEM images of CFB end (a) before polishing, and after polishing for the distances of (b) 200 m, (c) 600 m, and (d) 1000 m.

distance section between 200 and 600 m, the amplitude change ratio takes larger negative values for longer lapping distances. This suggests that a larger quantity of droplets has been removed. The spectral analysis results correspond with the reductions in the ten-point average surface roughness in **Fig. 12**. This may be attributed to the increase in the number of the contacts of the carbon fibers with the droplets as the lapping distance increases. In particular, the experimental results for the lapping distance of 600 m show the smallest amplitude change ratio in the entire wavelength range even if combined with the graph in **Fig. 15**, suggesting that a large quantity of droplets has been removed and that the surface has been made smoother. A comparison of **Figs. 7**, **8**, **12**, and **14** reveals the smoothest surface roughness for the lapping distance of 600 m.

The experimental results for the lapping distances of 800 and 1000 m show smaller amplitude change ratios than those for the lapping distance of 600 m, proving that the surface has become rougher, which corresponds with the arithmetic average roughness of the droplet-less area in **Fig. 14**. These experimental results also correspond with the AFM images in **Fig. 11**, where we can observe some deep lapping scratches for the lapping distances of 800 and 1000 m.

**Figure 19** shows the SEM images of the CFB surface before and after lapping. From this figure, we can observe that an increase in the lapping distance increases the transferred material, assumed to be derived from the ta-C coating, to cover the brush surface. Generally, clogging in the grinding process reduces the grind efficiency. However, the increase in the transferred material generates deep lapping scratches as shown in **Fig. 11**. ta-C coating, which is an extremely hard material, is known to produce a large amount of wear by its own worn debris in the friction process [34]. In this study, too, a similar phenomenon appears to have occurred, in which the transferred material derived from the hard ta-C coating cut the ta-C coating itself to cause large wear scratches. The lapping experiments revealed that brush-lapping hard ta-C coatings requires hard fibers such as carbon fibers and that, because of the aggression by the transferred material derived from the ta-C coating, brush-lapping for a long time degrades the surface profiles. The aforementioned experimental results show that CFB-lapping requires a process such as dressing a grind stone and that it is important to control its lapping distance appropriately.

## 5. Conclusions

This study revealed the lapping properties of a lapping brush made of carbon fibers, which is a material having excellent mechanical strength and flexibility due to its high aspect ratio. In this study, we revealed the lapping properties of CFB in lapping DLC coatings where, in particular, the removal of fine particles called droplets has remained an issue to be addressed.

The lapping experiments with CFBs of different brush lengths revealed that shorter brush lengths have a better droplet removal efficiency. However, we observed some deep lapping scratches on the surface lapped with CFBs of shorter brush lengths. The results of surface roughness measurement indicate that a CFB with excellent droplet removal properties and low opponent aggressiveness could be developed by increasing the brush length. Lapping with a CFB of brush length 12 mm, which is the longest in the experiments, generated a lapped surface with the ten-point average surface roughness $S_{ZJIS} =$ 75 nm and the arithmetic average surface roughness $S_a =$ 4.7 nm, which are 59% and 22% of those of the surface before lapping, respectively. This demonstrates the excellent lapping properties of the CFB. The arithmetic average roughness of the droplet-less area is $R_a = 0.70$ nm, which is approximately 0.3 nm larger than that before lapping (0.41 nm) but the area maintained a high level of smoothness of $R_a = 1.0$ nm or less even after lapping. The lapping experiments also revealed that a longer brush length can more effectively discharge the entire mass of droplets, demonstrating the effectiveness of CFB in lapping DLC coatings.

The lapping experiments for different lapping distances indicate that lapping for a lapping distance of 600 m produced the best lapping properties. We observed that shorter lapping distances left some droplets unremoved because the lapping time was not sufficiently long. On the other hand, longer lapping distances degraded surface profiles by accumulating a transferred material, which derived from the hard ta-C coating, on CFB surface. The smoothest surface generated by the lapping distance of 600 m exhibited the ten-point average surface roughness $S_{ZJIS} = 25$ nm, which is 86% better than that before lapping. The arithmetic average roughness of the droplet-less area $R_a = 0.43$ nm is nearly the same as that of the surface before lapping. Thus, this study demonstrated the excellent lapping properties of the CFB, which can selectively remove droplets.

**References:**

[1] A. Erdemir and C. Donnet, "Tribology of diamond-like carbon films: recent progress and future prospects," J. Phys. D: Appl. Phys., Vol.39, pp. 311-327, 2006.

[2] C. Donnet, "Recent progress on the tribology of doped diamond-like carbon alloy coatings: a review," Surf. & Coat. Technol., Vols.100-101, pp. 180-186, 1998.

[3] A. Erdemir, "The role of hydrogen in tribological properties of diamond-like carbon films," Surf. & Coat. Technol., Vols.146-147, pp. 292-297, 2001.

[4] M. Sonobe, "Application of DLC coatings to dry cutting tools," Tribologist, Vol.47, pp. 827-832, 2002 (in Japanese).

[5] M. Kano, "Diamond-like carbon coating applied to automotive engine components," Tribology Online, Vol.9, pp. 135-142, 2014.

[6] Y. Mabuchi, "Application of DLC coatings on automotive parts," Tribologist, Vol.58, pp. 557-565, 2013 (in Japanese).

[7] Y. Mabuchi, T. Yamashita, H. Izumi, T. Sekikawa, K. Nishimura, S. Hirano, and Y. Moriguchi, "Examination of the axial shape of the automotive valvetrain cam for engine friction reduction," Tribology Trans., Vol.60, pp. 1088-1098, 2017.

[8] T. Higuchi, Y. Mabuchi, H. Ichihara, T. Murata, and M. Moronuki, "Development of hydrogen-free diamond-like carbon coating for piston rings," Tribology Online, Vol.12, pp. 117-122, 2017.

[9] Y. Mabuchi, T. Higuchi, and V. Weihnacht, "Effect of sp2/sp3 bonding ratio and nitrogen content on friction properties of hydrogen-free DLC coatings," Tribology Int., Vol.62, pp. 130-140, 2013.

[10] H. Takikawa, K. Izumi, R. Miyano, and T. Sakakibara, "DLC thin film preparation by cathodic arc deposition with a super droplet-free system," Surf. & Coat. Technol., Vol.163, pp. 368-373, 2003.

[11] H. Takikawa, "Coating Technology of Droplet-free High-quality DLC Film by Filtered Arc Ion Plating," J. Surf. Finishing Soc. Jpn., Vol.58, pp. 572-577, 2007 (in Japanese).

[12] Y. Mabuchi, T. Higuchi, Y. Inagaki, H. Kousaka, and N. Umehara, "Wear analysis of hydrogen-free diamond-like carbon coatings under a lubricated condition," Wear, Vol.298, pp. 48-56, 2013.

[13] M. Murashima, X. Deng, H. Izuoka, N. Umehara, and H. Kousaka, "Effect of oxygen on degradation of defects on ta-C coatings deposited by filtered arc deposition," Surf. & Coat. Technol., Vol.362, pp. 200-207, 2019.

[14] X. Shi, B. K. Tay, H. S. Tan, E. Liu, J. Shi, L. K. Cheah, and X. Jin, "Transport of vacuum arc plasma through an off-plane double bend filtering duct," Thin Solid Films, Vol.345, pp. 1-6, 1999.

[15] R. L. Boxman, V. Zhitomirsky, B. Alterkop, E. Gidalevich, I. Beilis, M. Keidar, and S. Goldsmith, "Recent progress in filtered vacuum arc deposition," Surf. & Coat. Technol., Vol.86-87, pp. 243-253, 1996.

[16] Y. Fujii, T. Imai, Y. Miyamoto, N. Ueda, M. Hosoo, T. Harigai, Y. Suda, H. Takikawa, H. Tanoue, M. Kamiya, M. Taki, Y. Hasegawa, N. Tsuji, and S. Kaneko, "Dry machining of metal using an engraving cutter coated with a droplet-free ta-C film prepared via a T-shape filtered arc deposition," Surf. & Coat. Technol., Vol.307, pp. 1029-1033, 2016.

[17] A. Anders, "Approaches to rid cathodic arc plasmas of macro- and nanoparticles: a review," Surf. & Coat. Technol., Vol.120-121, pp. 319-330, 1999.

[18] M. Kamiya, T. Yanagita, H. Tanoue, S. Oke, Y. Suda, H. Takikawa, M. Taki, Y. Hasegawa, T. Ishikawa, and H. Yasui, "T-shape filtered arc deposition system with built-in electrostatic macro-particle trap for DLC film preparation," Thin Solid Films, Vol.518, pp. 1498-1502, 2009.

[19] H. Takikawa, "Fabrication of DLC film by filtered arc deposition," J. Plasma Fusion Res., Vol.92, pp. 466-471, 2016.

[20] A. Leson, G. Englberger, D. Hammer, S. Makowski, C.-F. Meyer, M. Leonhard, H.-J. Scheibe, and V. Weihnacht, "Diamond-like carbon thin films enhance efficiency – laser arc deposition of ta-C," Vakuum, Vol.27, pp. 24-28, 2015.

[21] M.-Y. Tsai, Y.-F. Lin, J.-K. Ho, and J.-G. Yang, "Ultrasonic-Assisted Innovative Polyurethane Tool to Polish Mold Steel," Int. J. Automation Technol., Vol.13, No.2, pp. 199-206, 2019.

[22] Y. Manabe, H. Murakami, T. Hirogaki, E. Aoyama, and T. Furuki, "Mirror-Surface Finishing by Integrating Magnetic-Polishing Technology with a Compact Machine Tool," Int. J. Automation Technol., Vol.13, No.2, pp. 207-220, 2019.

[23] U. Satake, T. Enomoto, T. Miyanaga, T. Ohsumi, H. Nakagawa, and K. Funabashi, "Stabilization of Removal Rate in Small Tool Polishing of Glass Lenses," Int. J. Automation Technol., Vol.13, No.2, pp. 221-229, 2019.

[24] A. Kubota, "Surface finishing of single-crystal SiC and GaN wafers using a magnetic tool in $H_2O_2$ solution," Int. J. Automation Technol., Vol.13, No.2, pp. 230-236, 2019.

[25] K. Miyake, "Characteristics and Applications of Diamond Like Carbon (DLC) Films," J. Vac. Soc. Jpn., Vol.60, pp. 428-436, 2017 (in Japanese).

[26] S. Otani, "Tansoshitsuseni," Tanso, Vol.1967, pp. 32-39, 1967 (in Japanese).

[27] T. Shitaka, M. Murashima, N. Umehara, Y. Tsukiyama, I. Nitta, H. Kousaka, and X. Deng, "Proposal of lightweight and low starting torque slide bearing with looped carbon fibers brush," Trans. JSME, Vol.83, pp. 1-10, 2017 (in Japanese).

[28] A. Fukunaga, "CMP souti to electrochemistry," Electrochemistry, Vol.74, pp. 971-975, 2006 (in Japanese).

[29] R. Ozawa, Y. Suzuki, N. Mori, T. Yaguchi, J. Itoh, and S. Yamamoto, "Surface Roughness Evaluation/Power Spectral Density and Slope Histogram," Surf. Sci., Vol.20, pp. 727-731, 1999 (in Japanese).

[30] M. Kato and K. Kutsuzawa, "Fukugouzai (CFRP) oyobi tainetsugoukinn no sessaku kakougijutu," Jisedai monodukuri kibankakougijutu chousa kakou data syuu, pp. 41-51, 2012 (in Japanese).

[31] H. Hanyu, "Diamond Coated Tools for Machining of Lightweight Materials," J. Surf. Finishing Soci. Japan, Vol.63, pp. 151-156, 2012 (in Japanese).

[32] T. Kumagai, "Recent Progress in DLC Coated Cutting Tool," J. Surf. Finishing Soci. Japan, Vol.51, pp. 250-254, 2000 (in Japanese).

[33] X. Huang, "Fabrication and Properties of Carbon Fibers," Materials, Vol.2, pp. 2369-2403, 2009.

[34] X. Li, X. Deng, H. Kousaka, and N. Umehara, "Comparative study on effects of load and sliding distance on amorphoushydrogenated carbon (a-C:H) coating and tetrahedral amorphous carbon (ta-C) coating under base-oil lubrication condition," Wear, Vols.392-393, pp. 84-92, 2017.



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