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RESEARCH ARTICLE

Improvement of Durability and Sliding Properties of Food Packaging Equipment by Combined Treatment of Diamond-Like Carbon Coating and Fine Particle Bombarding

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ABSTRACT

Recently, there is a demand for the development of an eco-friendly surface treatment technology that can replace PTFE coating and hard chrome plating, which are a common process for food packaging equipment. We intended to improve the sliding properties and wear resistance of food packaging equipment by the fine particle bombarding (FPB) process to a metal substrate and depositing diamond like carbon thin film under atmospheric pressure (AP-DLC). These treatments are eco-friendly and low-cost. The Stainless steel substrates treated by FPB showed better sliding properties than the mirror substrate. By FPB treatment, AP-DLC coating was successfully applied to steel substrates without peeling. Also, by coating AP-DLC on the FPB-treated substrate, the width of wear track after the sliding test was reduced by 20% compared to the mirror substrate, and the wear resistance was improved. These results indicate that the metal using the combined treatment of FPB and AP-DLC coating is a promising material for food packaging equipment.

KEYWORDS

Fine particle bombarding; Diamond-like carbon; Sliding properties; Wear resistance

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INTRODUCTION

Various foods such as powder and solid food, become commercial products through packaging equipment comprised of hoppers, shooters, conveyors, and filling/sealing machines. With the packaging equipment, troubles such as bridge phenomenon in the hopper and clogging of the sieve occur, causing a decrease in production efficiency and an increase in defective products. The main causes are poor sliding properties between food, packaging materials, and the metal surface of the equipment. In general, the metal surface contacted with such materials is treated with a polytetrafluoroethylene (PTFE) coating or the hard chrome plating to improve sliding properties and hardness. However, since the PTFE coatings easily wear and delaminate, concern about contaminated of PTFE into foods and safety of the human body has grown [1]-[3]. Also, the hard chrome plating generates effluents that contaminate the environment and requires wastewater treatment. Therefore, there is an urgent need for the development of an eco-friendly surface treatment technology that can replace PTFE coating and hard chrome plating.

In recent years, the Fine particle bombarding (FPB) process has attracted attention from the viewpoint of improving the sliding properties of metal parts. FPB is a method of projecting particles and brings large plastic deformation on the substrate surface [4], [5]. Plastic deformation causes the formation of micro-dimples on the substrate material surface and improves the sliding properties due to the reduction of the contact area. However, metal (steel) parts used for food packaging equipment has a problem in that its surface wears by long-term contact with the food or packaging materials. Even if sliding properties are improved by roughening the metal surface using FPB treatment, the metal surface becomes smooth due to wear and again, occurs sticking. Therefore, to improve the production efficiency of the food packaging equipment, there is a demand for a technique that gives both high sliding properties and high wear resistance to the material surface.

To achieve these requirements, we focused on the combined treatment of FPB and Diamond-like carbon (DLC) coating. The DLC coating is hydrogenated amorphous carbon (a-C:H) thin films having high hardness, excellent chemical durability and high wear resistance [6]. Also, Kumagai et al. reported that the friction coefficient of a metal substrate was reduced to about 0.1 by coating DLC on the FPB treated substrate [7], [8]. Unlike a plating process, the DLC coating is an environmentally friendly process because it does not use harmful substances during the synthesis. Wear of metal surface can be reduced by coating DLC thin films on the FPB treated metal surface. However, DLC coating generally needs vacuum equipment [9]. The processing area of vacuum equipment is small, thus coating the films on large metal parts such as food packaging equipment is complicated. Also, the vacuum technique costs a lot. Atmospheric pressure plasma-enhanced chemical vapor deposition (AP-PECVD) is a promising method to overcome the problems of processing area and cost, and it has been studied for more than a decade [10] - [16]. Recently, our research group reported that hard DLC coating applied by the AP-PECVD process (AP-DLC coating) achieved the hardness of around 10 GPa [17] - [19].

In this study, to improve the sliding properties and wear resistance of the food packaging equipment, FPB treatment and AP-DLC coating were applied to the metal surface. Stainless steel and carbon steel, which are common materials for food equipment, were used for the metal substrate. The effect of FPB treatment on the sliding properties of the metal surface and the influence of the combined treatment of FPB and AP-DLC coating on the wear resistance of metal were investigated.

MATERIALS AND METHODS

For evaluating the effects of FPB treatment on sliding properties of a material surface, a stainless steel 304 (SUS304) were used as substrates. A single-crystal Si (100) wafer was used to measure the hardness and the hydrogen content of the AP-DLC coatings. The effect of combined treatment of FPB and AP-DLC coating on wear resistance was evaluated using a carbon steel (S45C) substrate. Details are shown below.

FPB treatment

Preparation of SUS substrates

SUS 304 with a size of 150 × 200 mm and a thickness of 2 mm was used as a substrate to evaluate sliding properties. Figure 1 shows a schematic diagram of the FPB process. The substrates were roughened using a blast machine (Pneuma Blaster FDQ-2S-L101, Fuji Manufacturing Co., Ltd., Japan) with a particle projection speed of over 100 m/s, projection distance of 70 mm, and bombarding scan speed of 100 mm^2/s. The direct air pressure was set at 0.2 MPa. Two substrates with different surface roughness were prepared using the two types of spherical ceramic particles. The diameter of spherical ceramic particles used for Substrate A was <50 µm, and that for Substrate B was ten times larger than that used for Substrate A. After the FPB treatment, particles remaining on the substrates were removed with an airbrush, and subsequently, the substrates were cleaned using water and ethanol. The surface roughness and the average maximum height of the substrates were measured using a VK-X100 laser scanning microscope (Keyence, Japan) operated at an excitation wavelength of 658 nm.

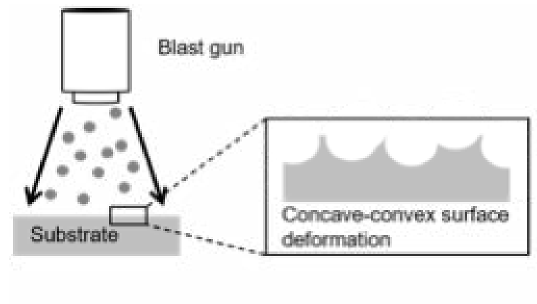


Fig. 1: Schematic diagram of the FPB process.

Preparation of S45C substrates

S45C with 30 mm x 30 mm in size and 5 mm thick and a Vickers hardness of 250 HV was used as a substrate to measure a wear resistance when treated the FPB and AP-DLC coating. The average initial surface roughness (R_a) of the mirror (control) substrates was 0.15 µm. The surfaces of the substrates were roughened by FPB using the same machine as above with spherical steel particles that were <47 µm in diameter, a particle projection speed of over 100 m/s, projection distance of 70 mm, and bombarding scan speed of 100 mm^2/s. The direct air pressure was set at 0.2, 0.3, 0.5, or 0.6 MPa to vary the surface roughness. Particles remaining on the substrates were removed with an airbrush. R_a was measured using a VK-9710 laser scanning microscope (Keyence, Japan) operated at an excitation wavelength of 408 nm. The dimensions of the concave and convex dimples were measured using a DektakXT surface profilometer (Bruker, U.S.A.), and the dimple diameter distributions were calculated using fast Fourier transforms.

Deposition of AP-DLC coating

A schematic diagram of the AP-PECVD apparatus is shown in Figure 2. The plasma was sustained between the parallel copper electrodes: the upper electrode, 100 × 10 mm^2 in size, was connected to a high-frequency power supply and covered with a 1-mm-thick alumina dielectric plate, and the lower electrode, 200 × 300 mm^2 in size, was grounded. The substrates were set on the lower electrode moving back and forth at intervals of 50 mm in the direction of plasma length at speeds of 0.1 mm/s in parallel to the upper one. The AP-DLC coatings were deposited from a gas mixture of a dilution gas and a source gas. He and Ar gases were used as the dilution gas, whose flow rates were 7.4 l/min and 1.8 l/min, respectively. CH_4 gas was used as a source gas whose flow rate was 800 ml/min. The gas mixture was introduced between the upper and the lower electrodes whose distance is 4.0 mm. The pulse frequency and input voltage between the electrodes were fixed at 30 kHz and 11 kV with a pulse width of 2 µs for plasma source. The thickness of the AP-DLC coating was 500 nm to sustain the shape of the surface roughened by FPB treatment.

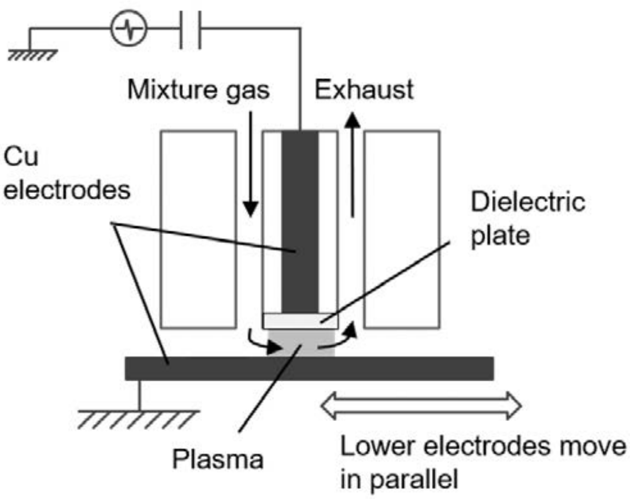


Fig. 2: Schematic diagram of the atmospheric pressure plasma CVD apparatus.

The hydrogen content of AP-DLC coating was analyzed using an HRBS1000 Rutherford backscattering spectrometer (KOBELCO, Japan) equipped with a N^+ ion beam. Measurements were performed at an acceleration voltage of 500 kV and an incident and scattering angle of 62.5°. The hardness of AP-DLC coating was measured using a nanoindentation tester (Nano Indenter® G200 system, TOYO Corporation, Japan) with a Berkovich diamond indenter. The indent load was 1.0 mN, and the load-displacement curve was analyzed using the Oliver and Pharr method [20]. The measurements of the hardness were performed at 10 different surface locations.

Static friction test of SUS substrates

The static friction coefficient was investigated on a contact angle meter (DMo-701, Kyowa Interface Science Co., Ltd., Japan). Figure 3 shows the image of the static friction test. The test specimen was placed on the sample stage with the SUS substrate, and the sample stage was tilted at 1-degree intervals. The angle at which the test specimen started to slide was recorded, and the static friction coefficient was calculated. Table 1 shows the details of the test specimens. The test was performed three times on each substrate and test specimen.

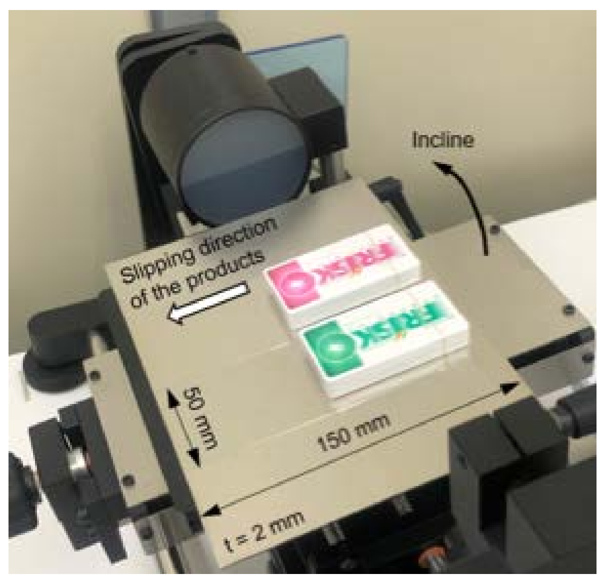


Fig. 3: Image of Static Friction Test.

Table 1: Details of test specimens

	Sample 1	Sample 2
Products	A Candy packaged with a polymer film. (FRISK, Perfetti Van Melle Japan, Japan)	
Measured size	70.5 × 36.7 ×10.9 mm	
Measured weight	70.85 g	80.84 g
Film material	Polypropylene	

Table 2: The average surface roughness and the average maximum height of each substrate.

	Mirror substrate	Substrate A	Substrate B
Average surface roughness (μm)	0.002	0.31	2.26
Average maximum height (μm)	0.01	2.23	14.05

Wear test of S45C substrates

The wear resistance was investigated on a ball-on-disk tribometer (CSM Instruments, Switzerland) using 6 mm (φ) SUJ2 balls. The sliding speed was 5 cm/s, and the load was increased at a rate of 3 N/min. The diameter of the sliding track was 5 mm. The sliding tests were carried out in ambient air with controlled 40-50% relative humidity and about 23 degrees Celsius temperature. The wear tracks after sliding were examined by scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) analysis on SEM (SEM Inspect S50, FEI, Japan).

RESULTS AND DISCUSSION

Effect of FPB on the sliding property of the metal surface

Table 2 shows the average surface roughness and the average maximum height of each sample. The surface roughness of Substrates A and B was 0.31 μm and 2.26 μm, respectively. Figure 4 shows the static friction coefficient of each sample. A low static friction coefficient indicates that the substrate surface has high sliding properties. The static friction coefficient on the mirror substrate was approximately 0.4 in both samples 1 and 2. The sliding properties of the substrates treated FPB was higher compared to the mirror substrate. In particular, Substrate B with a rough surface had a static friction coefficient of approximately 0.2, which indicated the best sliding property. It is considered that the increase in surface roughness caused the substrate and the polymer films to shift from entire surface contact to point contact, resulting in a decrease in the contact area. These results indicate that FPB treatment is an effective way of improving the sliding properties of the metal surface and suppressing the sticking of metal and polymer films.

Effect of combined treatment of FPB and

AP-DLC coating on wear resistance

Figure 5 shows the surface roughness of the S45C substrates as a function of the direct air pressure during FPB treatment. Figure 6 shows the dimple diameter distributions of each substrate. The diameter of most dimples on the substrate with R_a = 0.9 µm was approximately 20 µm. As the surface roughness increased to 1.4 µm, the distributions of the dimple diameter of the substrates increased to approximately 30 µm.

The hydrogen content of the AP-DLC coating was found to be 20%, and the hardness of the film was 7.7 GPa. This value was about the same value of hard chromium plating, which is conventionally used for a protective coating for metal parts [21]. Figure 7 shows the surface images of the AP-DLC deposited on the control substrate and the substrates following the FPB treatment. On the control substrate, the AP-DLC coating peeled off immediately after deposition. In contrast, the AP-DLC coatings could be successfully deposited on substrates treated FPB.

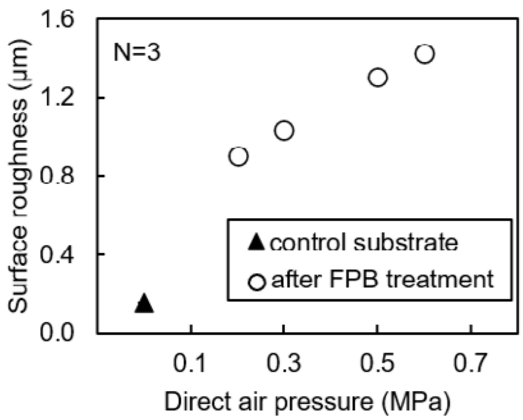
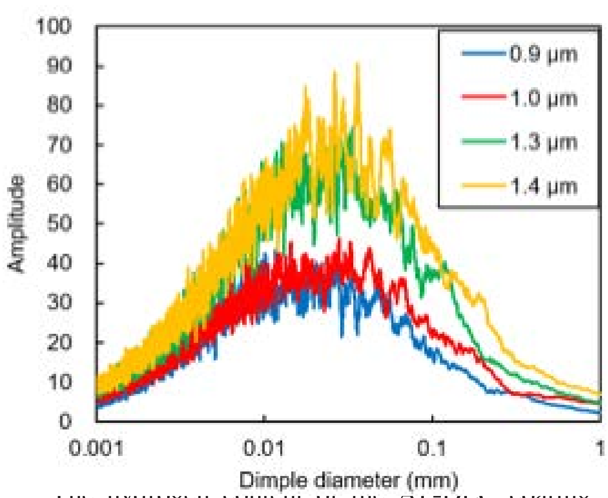


Fig. 5: The surface roughness of S45C as a function of direct air pressure.



The hydrogen content of the AP-DLC coating

Fig. 6: Distribution of dimple diameters on substrates with various surface roughness.

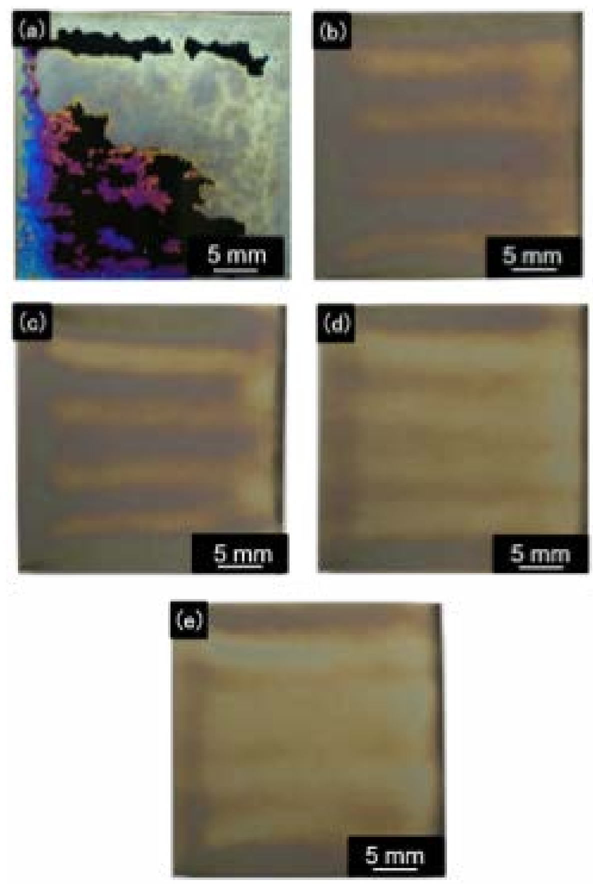


Fig. 7: Surface images of AP-DLC coatings on the substrates. a) control substrate. R_a: b) 0.9 µm, c) 1.0 µm, d) 1.3 µm, and e) 1.4 µm.

The wear tracks of the samples after the ball-on-disc tests are shown in the SEM images (Figure 8). For comparison, without the films, the control substrate and the substrate with R_a=1.0 µm were also evaluated. The widths of the AP-DLC coatings wear tracks on the S45C substrates with various surface roughness were measured via C and Fe EDX mapping. Figure 8 (a) (b) shows that the widths of wear tracks on the control substrate and R_a=1.0 µm substrate with no AP-DLC coatings were approximately 430 µm. Also, on the samples with R_a = 1.3 µm and R_a=1.4 µm with AP-DLC coating, broad wear tracks with a width of approximately 470 µm wide were observed, which indicates lower wear resistance than that of the control substrate. Figure 6 shows that the dimple diameter increases as the surface roughness increases. As the dimple diameter increases, the number of contact points with the SUJ2 ball decreases, and the load applied to the convex regions per point on the substrate surface could be to increase. It is considered that, on the samples with R_a = 1.3 µm and R_a = 1.4 µm, the wear resistance was decreased because the films delaminate easily due to an increase in the load to the convex region of the substrate surface. In contrast, on the sample with R_a= 0.9 µm, the width of the wear track was approximately 360 µm, which indicated that the wear resistance was improved as compared with the control substrate. Since the substrate surface with R_a=0.9 µm has a small dimple diameter (Fig. 6), the surface could have many contact points with the SUJ ball. It is considered that the wear resistance was improved because the load applied from the ball was dispersed over the entire sample, and the delamination of the AP-DLC coating was suppressed.

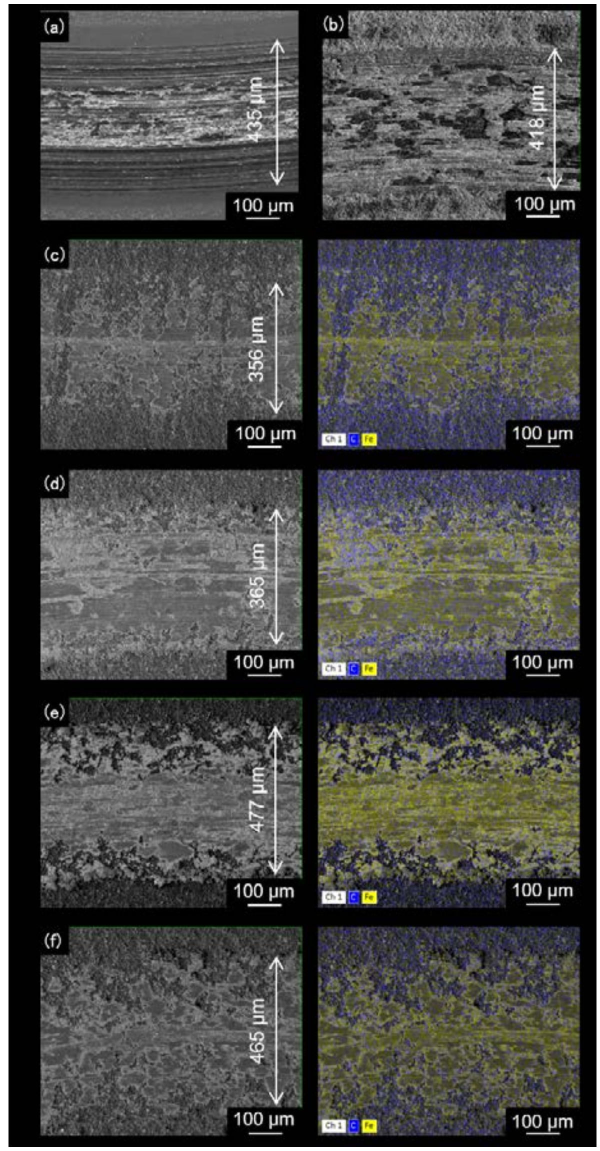


Figure 8. SEM images and EDX maps of wear tracks after ball-on-disk tests. a) Control substrate. b) Substrate with R_a = 1.0 µm. AP-DLC coatings on substrates with various R_as: c) 0.9 µm, d) 1.0 µm, e) 1.3 µm, and f) 1.4 µm. C (blue) and Fe (yellow) in the wear tracks are shown in the EDX maps.

CONCLUSIONS

In this study, we investigated the effect of FPB treatment on the sliding properties, and the effect of the combined treatment of FPB and AP-DLC coating deposited by AP-PECVD process on the wear resistance of the metal surface. By increasing the surface roughness of the substrates using FPB treatment, the sliding properties were improved between the substrates and the products with the polymer films. By FPB treatment, AP-DLC coating was successfully applied to steel substrates without peeling. Also, by depositing the AP-DLC coating on the substrate with R_a = 0.9 µm treated by FPB, the width of wear track after the sliding test was reduced from approximately 440 µm (the control substrate) to 360 µm. These results indicate that the combined treatment of FPB and AP-DLC coating is a promising and eco-friendly method to improve the durability and the sliding properties of food packaging equipment as an alternative to hard chrome plating and PTFE coating.

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