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Inhibitory Effect of the Sliding Surface Damage due to the Discharge

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ABSTRACT
The discharge traces on the surfaces of components, which are used in environments where oil or grease are abundantly supplied, are sometimes observed. It is a well-known fact that charge accumulation by the electric double layer is formed in the sliding surface, and that causes the discharge. Discharge causes small damage and promotes wear on the sliding surface. We developed a new DLC（Diamond-like Carbon）coating, and found that the coating had the effects of the damage suppression by discharge. This time, we report the results of detailed analysis of the tested DLC coating by TEM (Transmission Electron Microscope).

INTRODUCTION
It has been said that nuclear power generation is effective for reducing green-house gas which power plants produce by burning fossil fuels. However strong earthquake and Tsunami attacked Fukushima No. 1 nuclear power plants in March 2011 and radioactive materials which were emitted by hydrogen gas explosion contaminated wide area in northern Japan. Since then, almost all nuclear power plants have been suspended and wind power generation as well as solar photovoltaic generation have been popular in Japan[1),2)].

A wind power generation system mainly consists of a generator, a gear box and a propeller. Gear shafts of the gear box are supported by bearings. Therefore lubrication is very important for such bearings [1), 2)].

It has been reported that surface damage by electrostatics discharges are caused on the moving parts, to which a lot of lubricants are supplied [3)]. If wears caused as electrostatics discharges progresses, serious damages may occur to lead to downtime of the wind power generation.

Sasaki, et al. reported[4)] that static electricity generated by oil flow on the interface between the two moving parts which were lubricated and accumulated electricity would be discharged. If so, electrostatics discharge will be one of the reasons of surface damages on the interface of lubricated sliding surfaces.

The author reported[5] at the previous annual meeting that amorphous film which was formed by normal wear on the bearing surfaces might suppress wear by electrostatics discharges.

In order to demonstrate this hypothesis, the authors have developed a new method of DLC coating which is applicable to any types of surfaces. Electrostatics discharges were caused to the surface on which DLC was formed. The damaged surfaces were observed by SEM and TEM.

EXPERIMENTAL METHODS

1. Coating Test

DLC film was formed on the surface of bearing balls using the apparatus shown in Fig. 1.

For making the DLC film, an ionized vapor deposition was used. The used materials were the mixed gases of benzene and tetramethylsilane.

The DLC film was formed on the intermediate Si layer on the base metal of SUJ2 for improving the peel strength of DLC and the anti-wear property.

Figure 1. CVD/PVD film forming apparatus

The thickness of the DLC film was controlled to be 2μm. The DLC coating conditions are shown in Table 1.

For this experiment, the following three types of DLC were formed on the specimens: a conventional DLC-a, a lightly soft DLC-b having a low friction coefficient, and a DLC-c mixed with Si.

Table 1. Coating conditions

DLC-a	Filament current : 28 A, Anode voltage : 50 V Bias voltage : -2000 V Raw material gas : C_6H_6
DLC-b	Filament current : 28 A, Anode voltage : 50 V Bias voltage : -2800 V Raw material gas : C_6H_6
DLC-c	Filament current : 28 A, Anode voltage : 50 V Bias voltage : -2000 V Raw material gas : C_6H_6+$Si(CH_3)_4$
Intermediate layer	Filament current : 28 A, Anode voltage : 50 V Bias voltage : -2000 V Raw material gas : $Si(CH_3)$

2. Discharge Tests

The experiment of electrostatics discharges was conducted using the tailor-made electrostatics discharge apparatus.

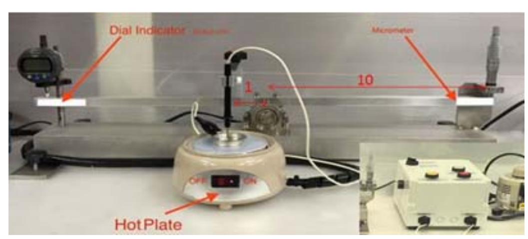

Figure 2. Electrostatics discharge apparatus

Electricity was accumulated in the capacitor of 4400 pF and the accumulated electricity was instantaneously discharged between a probe and a specimen of bearing ball. The discharged voltage was fixed to

1.5 kV and 0.05 kV respectively.

The gap between the probe and the specimen was controlled by the micro-gauge which was fixed to the arm of 1:10.

In order to reproduce the lubricated condition, ULTRA HMMF type CVT oil was coated on the surface of the specimen, which was placed on the hot-plate. The temperature of the hot-plate was controlled at 353 K.

DISCHARGE RESULT

Observation by SEM

The spot of the specimen, to which electrostatics discharge was caused, was confirmed by Scanning Electron Microscope (SEM) and cut by Focused Ion Beam system (FIB).

1. Discharge Test: 0.05 kV

Fig. 3 is the SEM image of the spot where electricity of 0.05 kV was discharged.

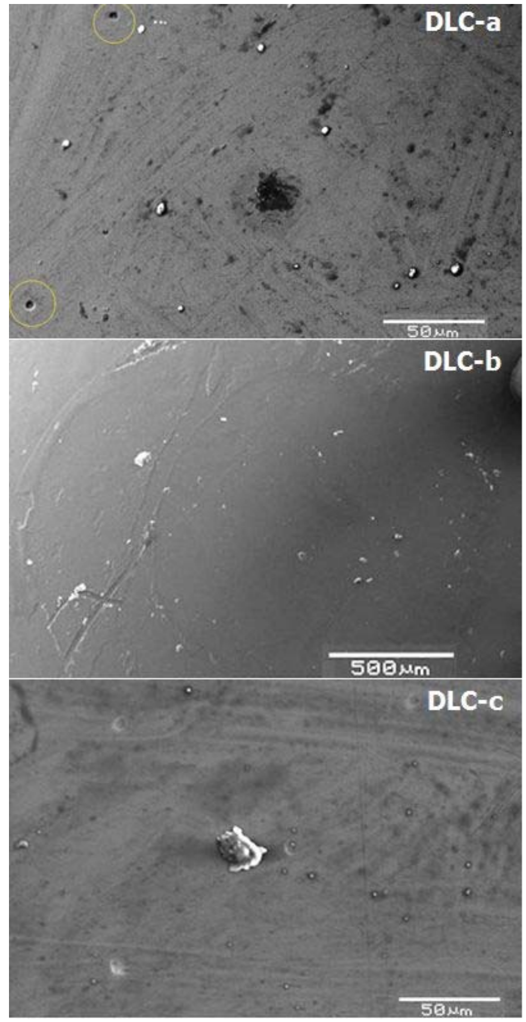

Figure 3. SEM Images of the spots of DLC-a, DLC-b and DLC-c where an electric discharge of 0.05 kV was hit.

No apparent damage was observed on the surfaces of all the conditions, to which electric discharges were caused by 0.05 kV, although damages were noticed on the specimens without DLC films, to which electric discharges were caused by 0.05 kV (5).

The pits in the yellow circles on the surface of DLC-a specimen were made when DLC film was formed. The Dimple at the center of the photo of DLC-c was examined by elementary analysis and was found to be a kind of debris.

2. Discharge Test: 1.5 kV

The SEM image of the DLC surface, on which electric discharge was hit by 1.5 kV, is shown in Fig. 4.

The damage by electrostatics discharge was the largest on the surface of DLC-a. Several pits were found in those area where a discharge was hit and the sizes of them were 50 μm to 100 μm in diameter. Additional evidence is needed to identify the pits to be metal melting parts

The image of DLC-b shows two damages caused by electrostatics discharges in narrow area.

The sizes of them were smaller than 30 μm in diameter. Comparing with the damages of DLC-a and DLC-c, the average sizes of the damages of DLC-b were smaller than those of the others and the numbers of damages were also fewer than those of the others.

The sizes of the discharge damages of DLC-c were as large as 100 μm in diameter. The damaged surface was removed by the discharge and the thickness of the layer became thin.

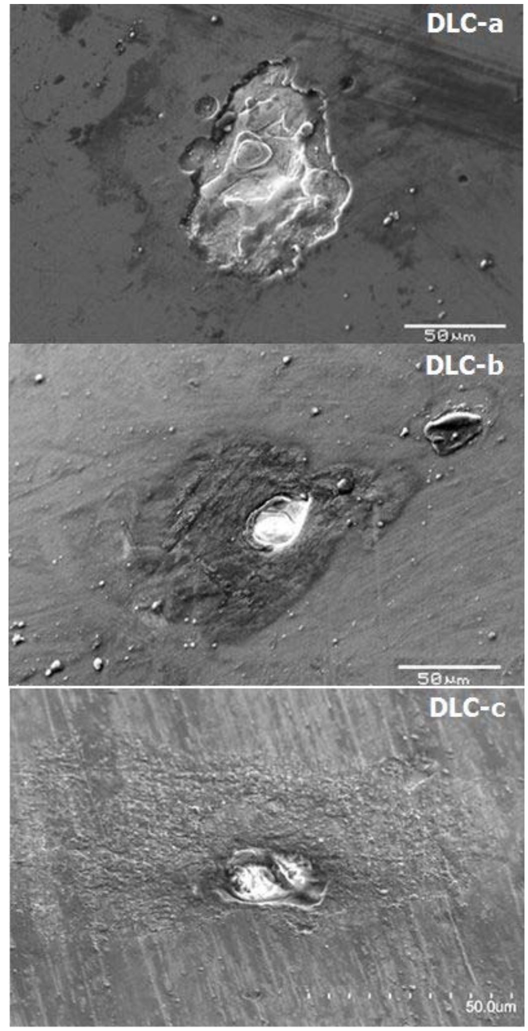

Figure 4. Examples of SEM Image of the Surfaces to Which Electric Discharge were Caused by 1.5 kV.

Observation by TEM

The parts of the typical damages by electric discharges were cut by FIB and observed by TEM.

Fig. 5 shows the SEM image of the damaged part, from which a sample was cut by FIB for TEM observation.

TEM sample cut by FIB is shown at the left and the upper corner of Fig. 5. TEM sample was observed by TEM. The TEM image is shown in Fig. 6.

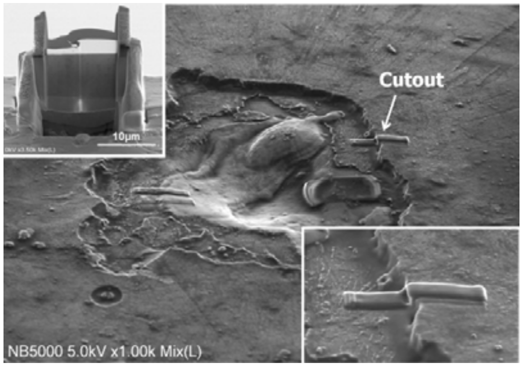

Figure 5. SEM Image of the Spot from which a Specimen was Cut by FIB (DLC-a).

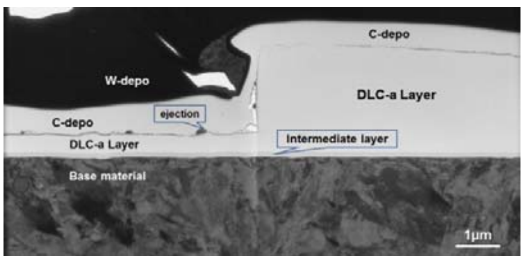

Figure 6. TEM Image of TEM sample of DLC-a.

The crack stops on the way of DLC film and the DLC film peels off horizontally there.

The further enlarged TEM image is shown in Fig. 7.

A structural disorder which was caused by heat was acknowledged at the upper part of the cracked DLC film.

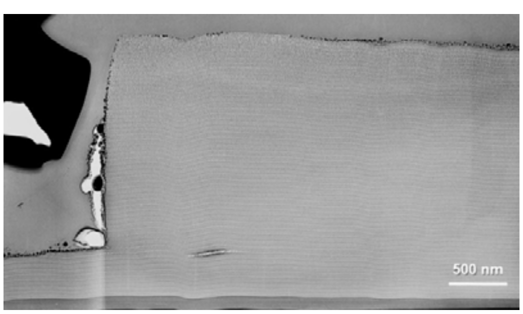

Figure 7. Further Enlarged TEM Image (DLC-a).

Fig. 8 shows the SEM image of the spot from which a specimen was cut by FIB (DLC-b).

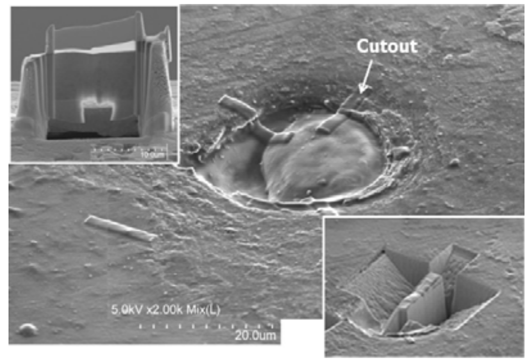

Figure 8. SEM Image of the Spot where TEM sample was Cut by FIB (DLC-b).

Fig. 9 shows the TEM image of TEM sample.

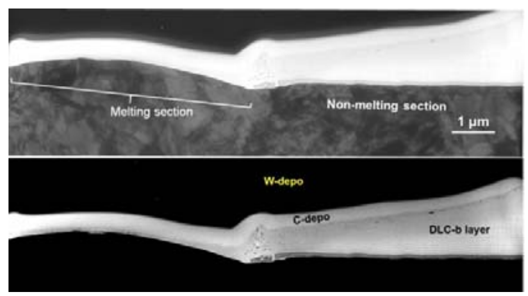

Figure 9. TEM Image of TEM sample cut by FIB.

The photo of the upper TEM image was taken with normal contrast. That of the lower TEM was taken with a special contrast to highlight the internal structure of the DLC film.

The left part of the surface shows that the base materials melted and that the DLC film became thin and was torn off. The right part of the surface looks unaffected by heat. Further enlarged TEM image is shown in Fig. 10.

It was found that DLC film is lapped in

way of the surface of the bump and that particles of carbon and iron, which may be originated by melting, are deposited.

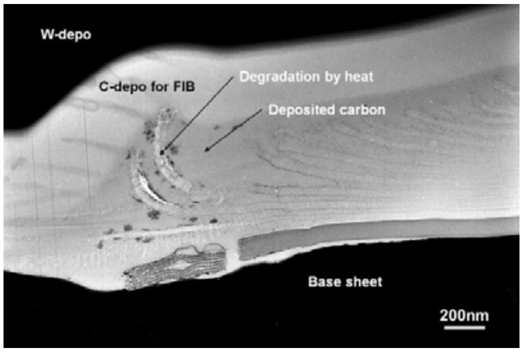

Figure 10. Further Enlarged TEM Image (DLC-b).

Fig. 11 shows the SEM image of the spot from which a specimen was cut by FIB.

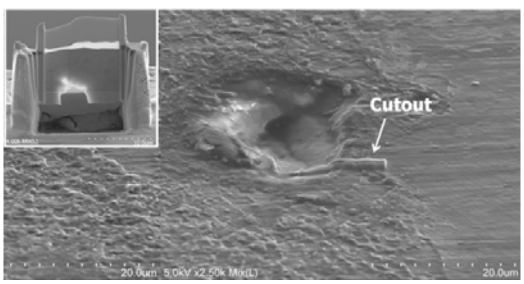

Figure 11. SEM Image of the Spot from Which a TEM sample was Cut by FIB.

The TEM image of TEM sample is shown in Fig. 12.

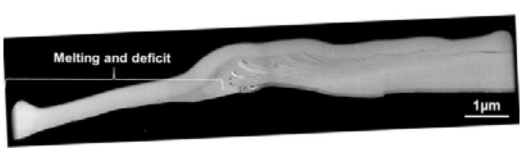

Figure 12. The TEM Image of TEM sample (DLC-c).

The left part of the TEM image shows that a part of DLC film is removed and the right part of the TEM image shows that the DLC film remains. It indicates that the crystal structure remains grain because the exposure of the surface to heat by electrostatics discharge was very short.

However it was found that fine structures in the DLC film disappeared. A further enlarged TEM image is shown in Fig. 13.

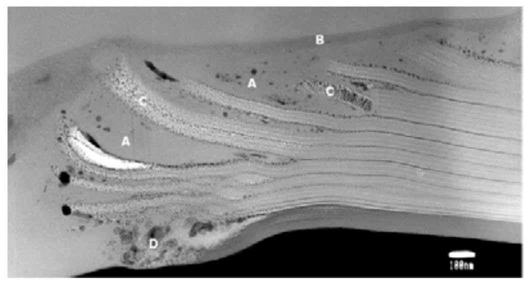

Figure 13. Further Enlarged TEM Image.

Fig. 13 shows that multi-layers exist in the DLC-c film, as they have Si and that the Si layers are peeling off.

The Area A also shows that the peeled layers lap that atoms and the fine particles, which were spattered by electrostatics discharges.

The Area B also shows that atoms and spattered particles are deposited in the surface.

The Area C shows that new breakages start at the end of the peeled layers

The Area D shows that the intermediate layer adjacent to the base material is damaged by exposure to heat.

DISCUSSION

DLC-a film is vertically and instantly damaged by the heat of the pulse-like electrostatics discharges and most of the discharged electrons go to the surface of the bearing base metal and melt it. It is considered that it happens because the DLC film is fragile mechanically.

In the cases of DLC-b and DLC-c films, they stand the heat shock. It is considered that the films maintained toughness.

Because of these, electrostatics discharge caused to rise the surface temperature suddenly and the heat decomposed the films. It is considered that the most of energy of electrostatics discharges did not conduct the bearing base metal by this mechanism and thus the anti-electrostatics discharge property was consequentially improved.

In the case of DLC film, the film was multiplied and the multiplied layers became easy to be peeled at the interface of each layer. Because of these phenomena, heat absorbing capacity was reduced comparing with that of DLC-~~b~~a and the anti-electrostatics discharge property was lowered slightly.

SUMMARY AND CONCLUSION

1. It was confirmed that the case of discharges voltage decreased to 50V, which can be generated by oil flow or the motion of two lubricated parts, could not cause any damages to the DLC film.

2. It was confirmed that the DLC-b film had an anti-discharge property equal to the electricity as high as 1.5kV, which can be generated by generators and batteries,

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