Performance Test of Diamond-Like Carbon Films for Lubricating ITER Blanket Maintenance Equipment under GPa-Level High Contact Stress

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(Received 20 July 2007 / Accepted 15 November 2007)

Diamond-like carbon (DLC) coating was tested as a candidate solid lubricant for transmission gears of the maintenance equipment of the blanket of the ITER instead of an oil lubricant. The wear tests using the pin-on-disk method were performed on disks with SCM440 and SNCM420 as the base materials and coated with soft, layered, and hard DLCs. All cases satisfied the required allowable contact stress (2 GPa) and lifetime (10^4 cycles), and therefore the feasibility of the DLC coating was validated. Among the three types of DLCs, the soft DLC showed the best performance.

Keywords: ITER, blanket, remote handling, diamond-like carbon, solid lubricant, gear, wear test, friction coefficient

DOI: 10.1585/pfr.2.052

A solid lubricant is preferable for the ITER blanket maintenance equipment, because an oil lubricant may have a negative influence on the plasma if it is left in the vacuum vessel during maintenance operations. Radiation hardness is another advantage of solid lubricants. However, it has been considered that conventional solid lubricants such as MoS_2 are not suitable for gears because high contact stress of GPa levels is applied on the teeth surface of the transmission gear, while the stress limit of the solid lubricants is just 0.6 - 0.7 GPa (60 - 70 kgf/mm^2) [1]. Recently, diamond-like carbon (DLC) has been used as a hard solid lubricant for magnetic storage media and sliding bearings [2], and has also been studied as a hard coating film for gears [3,4]. However, these studies used DLC coatings not as lubricants but as surface hardening materials for gears to enhance the surface contact fatigue life when polyester gear oils are used as lubricants. In the present study, DLC coating was tested as a candidate solid lubricant for the gears of the ITER blanket maintenance equipment instead of an oil lubricant because of its good mechanical, electrical, and chemical characteristics, including its hardness to resist high contact stress and low friction to enable smooth rotation of gears. The physical properties of the DLC can be changed to obtain DLC coatings as hard as diamond or as soft as graphite by varying the production conditions such as the bias voltage. It is also possible to obtain laminated coatings consisting of selected soft and hard DLC layers. The present study aims to validate the feasibility of a DLC coating as a solid lubricant for gears and to determine the required hardness of the DLC as a coating material under high contact stress by performing wear tests using flat plates coated with three different types of DLC coating. Considering the design requirements of the maintenance equipment in the ITER, the required values of allowable contact stress and lifetime were set as 2 GPa and 10^4 cycles, respectively. This high contact stress is caused due to the limitations on the width of the gears (minimized because of the limited space in the vacuum vessel of the ITER) and the heavy load capacity of the manipulator (lifts a component called "blanket module" weighing 4.5 tons). The lifetime of 10^4 cycles corresponds to one maintenance cycle of full replacement, in which 440 blanket modules are replaced and each replacement requires 14 rotations of the gear ($440 \times 14 \times 1.5 = 9,240 < 10^4$), considering a safety factor of 1.5. Two types of steel commonly used as base materials of gears were tested as candidate gear materials in the real machine. The difference in the results caused by the base materials is also studied in the present study.

A pin-on-disk-type friction and wear testing machine (TRAS300, Takachiho Seiki Co. Ltd.) was used in this study. Figure 1 shows a schematic view of the wear tests using the pin-on-disk method. A pin was pushed on a rotating disk with a certain vertical force and the tangential force induced on the pin was measured. The vertical and tangential forces are logged by a pen recorder. The pin was made of the same base material as the disk; however, it was not coated with DLC. This combination is similar to a pair of gears in an actual reactor: one is DLC-coated and the other is uncoated. The diameter of the pin was 11.3 mm and the radius of the top of the pin was 4 mm. The disk was 139 mm in diameter and 6 mm in thickness. The pin was placed at 60 mm from the center of the disk. The Hertzian

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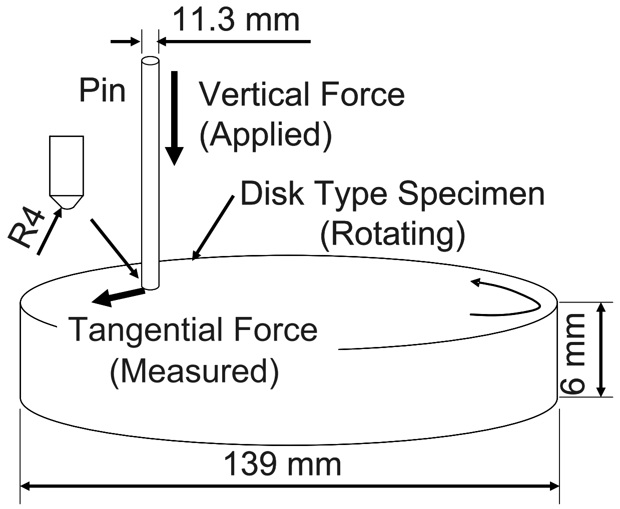


Fig. 1 Schematic view of the wear test. A pin is pushed on a rotating disk (specimen) with a certain vertical force and a tangential force induced on the pin is measured.

Table 1 Thickness and plastic hardness of DLC coatings measured with test plates using a calotester and nano indenter, respectively.

	Bias voltage	Thickness	Plastic hardness
Soft	50 V	2.2 μm	17.7 GPa
Layered	0–150 V (iterative)	2.0 μm	35.6 GPa
Hard	180 V	1.8 μm	57.7 GPa

contact areas between the pin and the disk were 0.01 and 0.28 mm^2 for vertical forces of 9.8 and 980 N, respectively. Two types of tests were performed: one aimed to obtain the wear load and a friction coefficient and the other aimed to obtain the lifetime.

The deposition of the DLC coatings was performed at Kobe Steel Ltd. (Takasago, Hyogo) using the unbalanced magnetron sputtering (UBMS) method [5], which is a type of physical vapor deposition that controls the film hardness via the bias voltage [6]. Three types of DLC were processed with different substrate bias voltages. The thickness and plastic hardness of each DLC coating on the test plates, which are processed at the same time as the disks, are summarized in Table 1.

The base materials used for the disk were SCM440, chromium molybdenum steel, and SNCM420, nickel chromium molybdenum steel, because their tensile strengths were relatively higher (~980 MPa) among widely used materials for gears. The disks were machined to a surface finish of $R_{max} < 3$ μm and then surface processed. The type of surface processing performed for the disk before the DLC coating process were the same as that for the gear material in the ITER design. The measured surface roughness and Vickers hardness of the pins and the disks are summarized in Table 2. The measurements for the disks were performed before the coating process. The number of tests performed on each disk is also shown in Table 2.

Figure 2 illustrates an example of a pen recorder chart of a wear load test. The wear load test was performed as follows. At the beginning of each trial, an initial vertical force of 9.8 N was applied and maintained for five minutes. Then, the vertical force was gradually increased to 980 N in increments of 98 N, each maintained for three minutes. The maximum vertical force of 980 N, which induces a Hertzian stress of 5.3 GPa, is sufficient for this study, because the stress is large enough compared to the design value of 2 GPa. The rotation speed of the disk was 100 rpm. In the wear load test, the Hertzian stress induced by the wear load of the DLC coating was considered as the allowable contact stress. The wear load was defined as the vertical load, which induced a tangential load higher than 196 N. The friction coefficient was determined as the ratio of the measured tangential force to the vertical force applied in the first step. The allowable contact stress and the friction coefficient are shown as functions of the hardness of DLC coating in Figs. 3 and 4, respectively. As shown in Fig. 3, the allowable contact stress was larger than the required value (2 GPa) in all cases. Among the three types of DLC, the soft DLC showed relatively higher values than the other two. As shown in Fig. 4, the friction coefficient was approximately 0.2 in all the cases, which is consistent with a previous study using DLC-coated steel [7], in which the coefficient was 0.18. No clear dependency on the hardness was observed. Regarding the difference in the base materials, SCM440 always showed lower values compared with SNCM420 for both the allowable contact stress and the friction coefficient, as shown in Figs. 3 and 4.

The lifetime test was performed as follows. The disk was rotated under a constant vertical force until the tangential force exceeded 196 N, and the duration of the test was defined as the lifetime. The rotation speed of the disk was 100 rpm and the maximum test period for each trial was 100 minutes, which corresponded to the required value of lifetime (10^4 cycles). The result is shown in Fig. 5. In all the cases, the DLC coating lasted until the required lifetime under a contact stress of 2.5 GPa, which was greater than the required contact stress. Among the three types of DLC, the soft DLC showed a relatively longer lifetime than the other two. As shown in Table 1, the soft DLC is 10% thicker than the layered DLC and 20% thicker than the hard DLC. In general, the lifetime should be proportional to the thickness. However, the difference in the lifetime shown in Fig. 5 cannot be explained by the thickness; for example, the lifetime of the soft DLC on SCM440 is 930 cycles under a vertical load of 3.9 GPa, while that of the other two is 100 cycles. Regarding the difference of the base materials,

Table 2 Surface roughness and Vickers hardness of the pins and the disks (before coating). The number of tests performed is also summarized.

Base material		Pin		Disk				
	Surface process	Roughness (<3)	Vickers hardness (>650)	Roughness (<3)	Vickers hardness (>650)	DLC	No. of tests	
							Wear load	Lifetime
SCM 440	Nitriding	1.5 μm	Hv 672	2.6 μm	Hv 708	Soft	3	1
						Hard	3	1
						Layered	3	1
SNCM 420	Carburizing and quenching	2.0 μm	Hv 889	1.9 μm	Hv 882	Soft	3	3
						Hard	3	3
						Layered	3	3

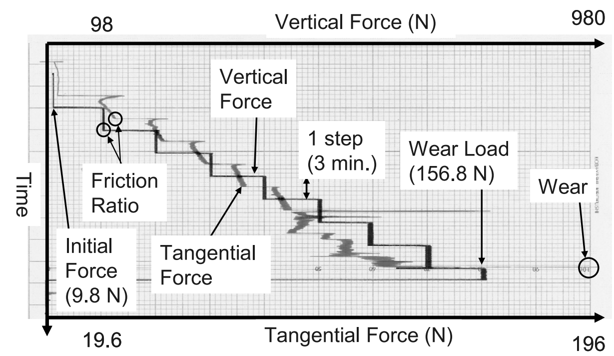


Fig. 2 Example of pen recorder charts. The lines for vertical and tangential forces are slightly shifted for better visibility.

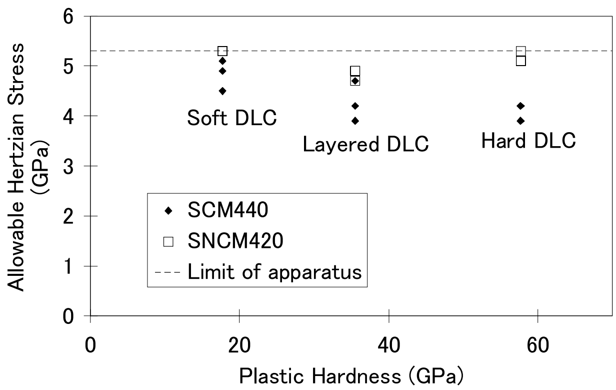


Fig. 3 Plastic hardness of DLC vs. allowable Hertzian contact stress. Three samples were tested for each combination of two base materials and three types of DLC. The limit of the apparatus was 5.3 GPa, which corresponded to 980 N.

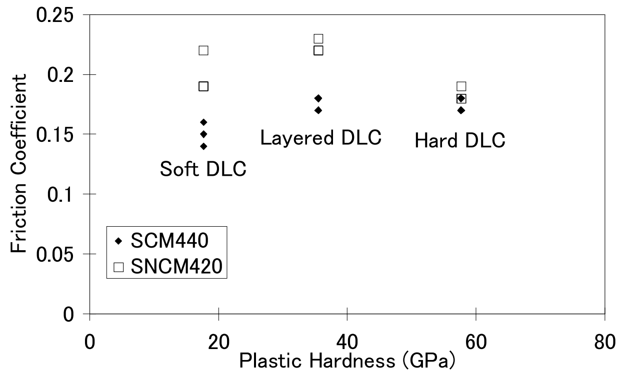


Fig. 4 Plastic hardness of DLC vs. friction coefficient. Solid diamonds represent results for SCM440 and open squares represent results for SNCM420. Three samples were tested for each combination of two base materials and three types of DLC.

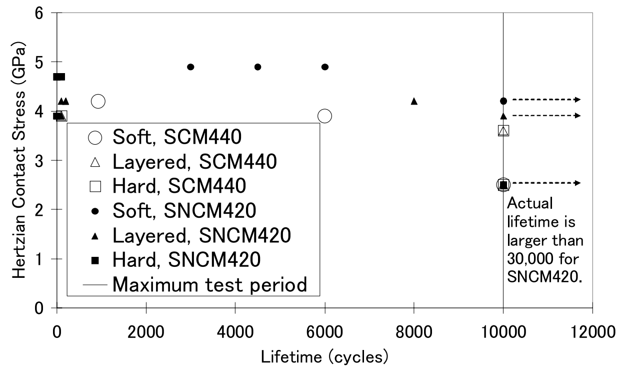
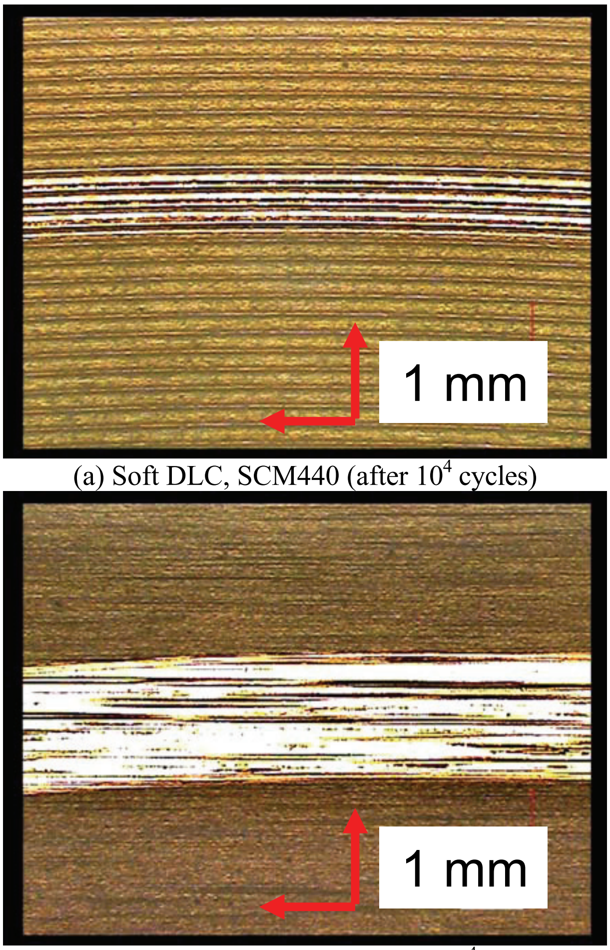


Fig. 5 Lifetime vs. Hertzian contact stress. Three samples were tested for each type of DLC on SNCM420, while one sample was tested on SCM440. For SNCM420, the test with the stress of 2.5 GPa was continued until 3×10^4 cycles, but the results were plotted for 10^4 cycles to allow comparison.

SNCM420 always showed a longer lifetime than SCM440. For SNCM420, the test with the Hertzian contact stress of 2.5 GPa was continued until 3×10^4 cycles in total, and all types of DLC lasted until the end of all the tests.

The results of the wear load test and the lifetime test showed that all the combinations of the two base materials and three types of DLC satisfied the allowable contact stress (2 GPa) and the lifetime (10^4 cycles). Among the



(a) Soft DLC, SCM440 (after 10^4 cycles)

(b) Soft DLC, SNCM420 (after $3x10^4$ cycles)

Fig. 6 Surface of the disks after the lifetime test. Although the test periods were different, the effect of the surface roughness could be observed.

three types of DLC, the soft DLC showed the best performance. It was considered that the peeled layers of DLC coating facilitate smooth sliding. Regarding the base material, the reason why SNCM420 showed better performance than SCM440 can be explained by the following two factors. One is the surface roughness of the base material. Figure 6 shows the surface of the disks coated with the soft DLC. As shown in Table 2, the surface of SCM440 was rougher than that of SNCM420, and the difference in the roughness could also be observed in Fig. 6. The coating on SNCM420 was exfoliated uniformly, while the exfoliation occurred locally at the peaks of the uneven surface of SCM440. Therefore, the wear load decreased for SCM440 because it was locally concentrated on the peaks where the contact stress increased. The other factor is the hardness of the base material. As shown in Table 2, the hardness of SCM440 was lower than that of SNCM420, and the deformability of the base material could affect on the wear. The effect of the surface roughness is supported by Fig. 6, while the effect of the hardness of the material is unclear. Therefore, the roughness factor seems convincing. However, the dominant factor between the two cannot be determined from these observations.

In summary, the disks with SCM440 and SNCM420 as base materials and coated with soft, layered, and hard DLCs satisfied the required allowable contact stress and lifetime in the wear test, and therefore the feasibility of the DLC coating was validated. Among the three types, the soft DLC showed the best performance, and therefore it is selected as a primary candidate for the coating material in further investigations. Regarding the base material, this study could not determine the better material, because the performance of the materials seemed to be affected by several factors other than the type of material used. In any case, it was clarified that both materials satisfied the required specification, and therefore, either of the two tested base materials can be used as the base material for gears, depending on the other requirements such as strength of gears and cost. DLC coating will be investigated further using the tested base materials in future studies.

[1] K. Obara *et al.*, Fusion Eng. Des. **10**, 495 (1989).
[2] R. Hauert and U. Müller, Diam. Relat. Mater. **12**, 171 (2003).
[3] C. Mercer *et al.*, Surf. Coat. Technol. **173**, 122 (2003).
[4] J.C. Jiang *et al.*, Surf. Coat. Technol. **176**, 50 (2003).
[5] B. Window and N. Savvides, J. Vac. Sci. Technol. A **4**, 196 (1986).
[6] K. Takahara *et al.*, KOBELCO Technology Review **26**, 81 (2005).
[7] V.N. Inkin *et al.*, Diam. Relat. Mater. **9**, 715 (2000).