Sliding Properties of Hydrogen-Free DLC under Sliding-Rolling Contact Condition

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As the electrification of automobiles progresses, the number of parts used in rolling and sliding environments, such as gears and bearings, which are often used in motors and reducers, is increasing. Therefore, improving their durability and reducing their friction loss are considered to be important. We coat various diamond like carbon (DLC) depending on the application. Among them, it has been confirmed that hydrogen-free DLC has a high friction reduction effect in lubricating oil. In this study, we investigated changes in durability when applying hydrogen-free DLC to gears and the friction reduction effect of hydrogen-free DLC in rolling and sliding environments. As a result, it was confirmed that coated gears with hydrogen-free DLC improve their durability. It was also confirmed that the friction reduction effect of hydrogen-free DLC is higher in environments with "lower viscosity of oil," "higher rotation speed," and "higher slip ratio."

Keywords: hydrogen-free DLC, gear, rolling-sliding, low viscosity

1. Introduction

The use of diamond-like carbon (DLC*1) in automotive applications has so far been primarily for engine parts with the aim of improving fuel efficiency, with importance placed on reducing friction in sliding environments. As the electrification of automobiles advances in the future, it is highly likely that reduced friction of parts used in rolling and sliding environments, such as gears and bearings which are heavily used in motors and reducers, will become important.

Nippon ITF Inc. uses various DLC coatings depending on the applications. Among these, the friction reduction effect of hydrogen-free DLC is specifically high in lubricating oil.[1] Therefore, changes in the durability of gears attributable to the coating of hydrogen-free DLC and their sliding properties in rolling and sliding environments have been studied.

2. Hydrogen-free DLC

2-1 Overview of hydrogen-free DLC

DLC is an amorphous film, mainly composed of carbon. The film is comprised of a diamond structure (sp^3 structure) and a graphite structure (sp^2 structure). Various properties are available depending on the sp^2/sp^3 ratio and hydrogen content in the structures. As a conceptual diagram of DLC films based on these percentages, A. C. Ferrari and J. Robertson proposed a ternary phase diagram (Fig. 1).[2]

The ta-C*2 and a-C*3 films with low hydrogen content illustrated in the ternary phase diagram are generally called "hydrogen-free DLC."

DLC films are formed through a process using either hydrocarbon gas or solid graphite. The common process carried out to form hydrogen-free DLC is the graphite process. Industrially, either vacuum arc deposition or sputtering is employed.

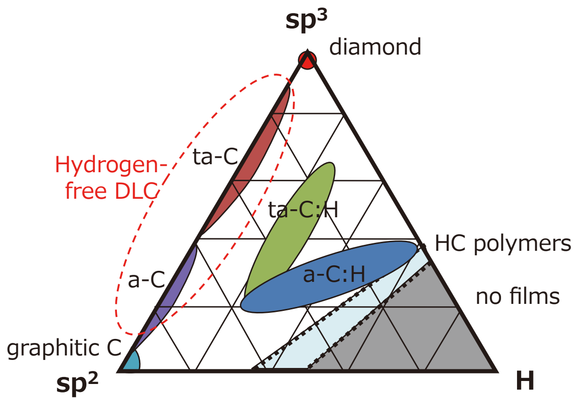


Fig. 1. Ternary phase diagram of DLC

2-2 Vacuum arc deposition

Nippon ITF forms hydrogen-free DLC by vacuum arc deposition. Vacuum arc deposition is a coating process that forms thin films by depositing high-energy ions emitted from cathode spots occurring on the surface of the cathode. The vaporized material from the solid cathode forms plasma, eliminating the need to introduce a hydrocarbon gas as a raw material for the thin films. This enables hydrogen-free DLC to be formed. However, vacuum arc deposition presents the problem of graphite particles being emitted from cathode spots. Emitted graphite particles deposit on the surface of the DLC being formed, resulting in the formation of cone-shaped DLC particles known as "droplets". These droplets are as hard as the DLC film itself. Therefore, they damage the mating part during sliding. On top of that, if they break off, they will damage the DLC film as well. For this reason, the surfaces of DLC films formed by vacuum arc deposition are often polished for use, to remove protrusions of droplets.

2-3 Filtered vacuum arc deposition

In vacuum arc deposition, a technique known as "filtered vacuum arc (FVA) deposition" has long been used to separate graphite particles produced at the cathode from carbon ions, the raw material of DLC films, thereby reducing the occurrence of droplets. A DLC film with few droplets can be formed by bending plasma produced from the cathode by a magnetic field and separating the plasma from the graphite particles, as shown in Fig. 2.

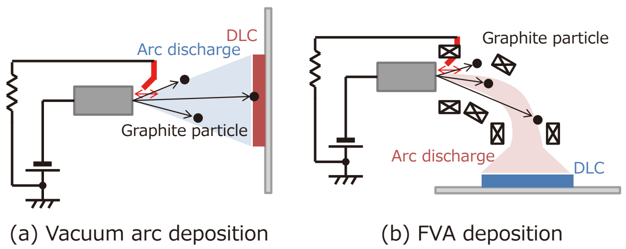


Fig. 2. Schematic image of film-forming processes

2-4 Properties of hydrogen-free DLC

Table 1 presents the properties of the hydrogen-free DLC films being tested. The film surface of DLC 1 formed by vacuum arc deposition was polished after forming in order to remove droplets. DLC 2 and DLC 3, formed by the FVA process, were tested without polishing after the film was formed.

Table 1. Production processes and properties of hydrogen-free DLC

	DLC 1	DLC 2	DLC 3
Coating method	Vacuum arc deposition	FVA deposition	
Film thickness	0.5 μm	1.0 μm	1.0 μm
Surface roughness Ra	0.018 μm (Polished)	0.028 μm (Unpolished)	0.031 μm (Unpolished)
Hardness	61 GPa	28 GPa	16 GPa
Young's modulus	555 GPa	317 GPa	149 GPa

3. Durability Testing of Gears

3-1 Test method

Durability testing of gears was conducted using an IAE power circulating-type gear testing machine (Fig. 3, Tables 2 and 3). The durability of the gears was evaluated, defining pitting fatigue life as the number of cycles at which the area of pitting*4 that occurred on the gear tooth face due to testing reached 1% of the entire contact surface.

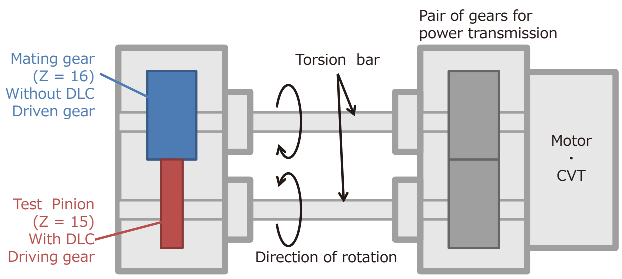


Fig. 3. Schematic diagram of IAE power circulating-type gear testing machine

Table 2. Gears Used in the Test

	Test Pinion	Mating gear
DLC	Coated	Uncoated
Material	SCM420 Young's modulus: 206 GPa Poisson's ratio: 0.3	
Number of teeth	15	16
Face width	5 mm	18 mm

Table 3. Test Conditions

Rotation speed		1800 rpm
Maximum Hertzian contact stress*5		1.8 GPa
ATF oil*6	Temperature	80°C±5°C
	Feed rate	750 mL/min
	Density	0.863 g/cm^3
	Flashing point	194°C
	Kinematic viscosity	33.03 mm^2/s @40°C 7.013 mm^2/s @100°C
	Viscosity index	181

3-2 Pitting fatigue life

Figure 4 shows the pitting fatigue life evaluated through the durability testing of gears. Compared to uncoated gears, all the gears coated with hydrogen-free DLC improved in terms of pitting fatigue life. In particular, the pitting fatigue of DLC 3-coated gears improved considerably over that of uncoated gears by a factor of 6.9.

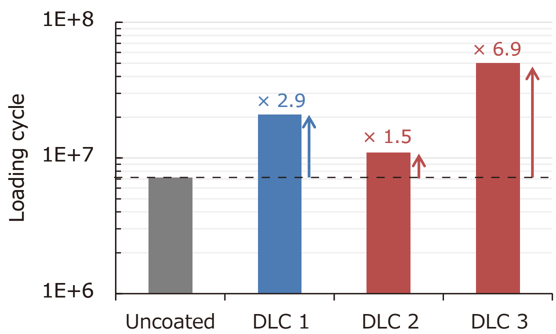


Fig. 4. Pitting fatigue life

3-3 Peeling resistance

Figure 5 presents the observation results of the tooth face condition at 7 × 10^6 loading cycles, to compare damage to each type of gear. The DLC 1 tooth face showed many scratches developing in the sliding direction. In contrast, the DLC 2 and DLC 3 tooth faces were free from scratches developing in the sliding direction. Although DLC 1 was polished after the coating, many droplets remained in the film. Therefore, it is highly probable that they broke off and caused scratches. On the other hand, DLC 2 and DLC 3, formed by the FVA process, contained few droplets, which highly likely contributed to the reduction in scratches caused by droplets.

Moreover, Fig. 5 reveals that different DLC films had different peeling conditions. The percentage of peeling area in the entire contact area, termed the "peeling area percentage," was calculated. Comparing the calculations to the Young's modulus of the DLC films revealed a correlation, as shown in Fig. 6. The Young's modulus of DLC 3, which had the least peeling, was lower than the Young's modulus of the substrate. It is highly likely that when the substrate deformed, DLC 3 also deformed following the deformation of the substrate, contributing to reduced peeling. It is also highly probable that the continued presence of DLC on the tooth face maintained good slidability, contributing to extending the pitting fatigue life.

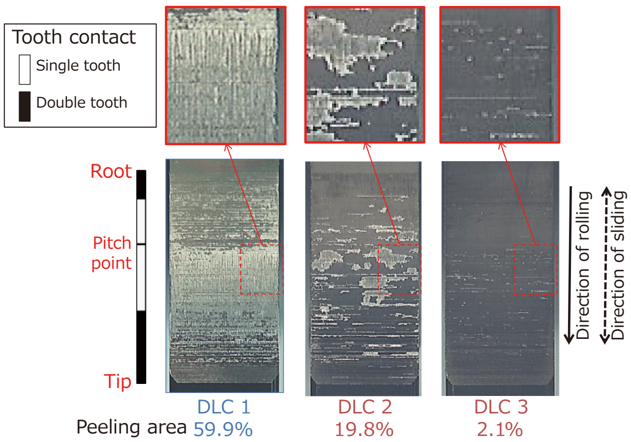


Fig. 5. Tooth damage condition (at 7 × 10⁶ cycles)

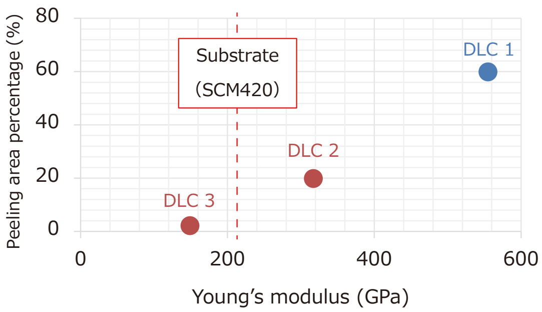


Fig. 6. Comparison of Young's modulus of DLC and peeling area percentages (at 7×10^6 cycles)

4. Rolling-Sliding Test

4-1 Test method

The friction coefficient of the most durable DLC 3 was evaluated with a rolling-sliding testing machine (Fig. 7, Tables 4 and 5). This tester rotates a ball and a disk at different speeds, thereby enabling rolling-sliding testing to be conducted at a desired rotation speed and slip ratio.

In the rolling-sliding test, first, break-in step was performed for 20 minutes to reach a stable temperature. This was followed by Stribeck measurement, intended to observe changes in the friction coefficient at varying speeds. The test further continued into traction measurement to observe changes in the friction coefficient at varying slip ratios. In these processes, machine oil and engine oil were used as lubricating oil. During use, the machine oil temperature was set to 40°C and the engine oil temperature was set to 100°C.

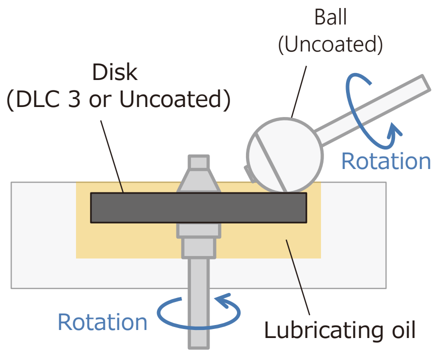


Fig. 7. Rolling-sliding testing machine

Table 4. Test Samples

Disk	SUJ-2 (DLC 3 or Uncoated)
Ball	SUJ-2 (Uncoated)
Lubricating oil	Engine oil (SN/GF-5, 5W-30) @100°C ⇒ Kinematic viscosity: 10.42 mm^2/s Machine oil (ISO GV46) @ 40°C ⇒ Kinematic viscosity: 46 mm^2/s

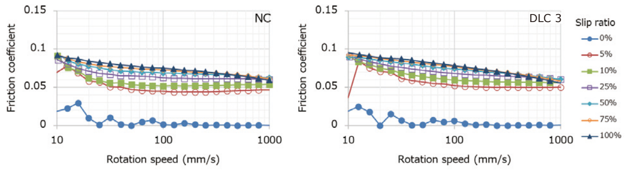
Table 5. Rolling-Sliding Test Conditions

	Step1	Step2	Step3
	Break-in step	Stribeck measurement	Traction measurement
Rotation speed	100 mm/s	1 mm/s ~ 1000 mm/s	
Slip ratio	0%	0% ~ 100%	
Load	0.5 N	37 N (Maximum Hertzian contact stress: 1.0 GPa)	
Note	20 min	Increased rotation speed	Increased slip ratio

4-2 Stribeck measurement

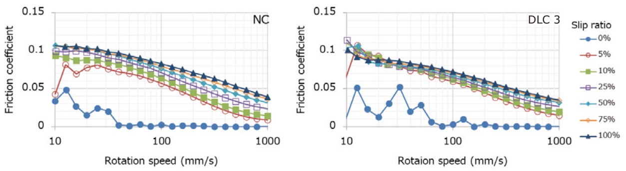
Figures 8 and 9 give the results of the Stribeck measurement. The slip ratio was difficult to control at rotation speeds of less than 10 mm/s, resulting in unstable measurements; therefore, the measurement results obtained at 10 mm/s or more are plotted.

Uncoated samples (NC) and DLC 3 showed little difference in friction coefficient in high-kinematic-viscosity lubricating oil (machine oil at 40°C). In contrast, in low-kinematic-viscosity lubricating oil (engine oil at 100°C), the friction coefficient of DLC 3 was lower than that of NC with increasing rotation speed and slip ratio.



(a) Measurement results for NC (b) Measurement results for DLC 3

Fig. 8. Stribeck measurement results (machine oil at 40°C)

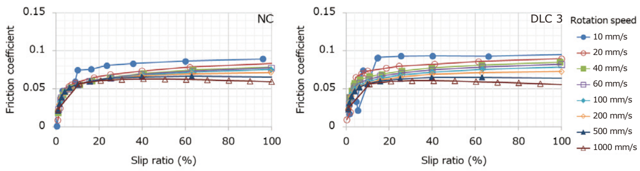


(a) Measurement results for NC (b) Measurement results for DLC 3

Fig. 9. Stribeck measurement results (engine oil at 100°C)

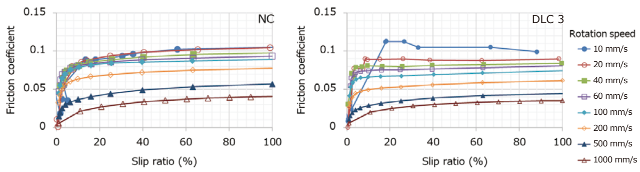
4-3 Traction measurement

Figures 10 and 11 plot the results of traction measurement. The traction measurement results also revealed that, although in high-kinematic-viscosity lubricating oil, the friction coefficient on DLC 3 was not lower than that on NC, the friction coefficient of DLC 3 was lower in low-kinematic-viscosity lubricating oil.



(a) Measurement results for NC (b) Measurement results for DLC 3

Fig. 10. Traction measurement results (machine oil)

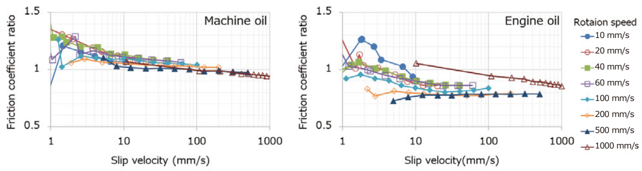


(a) Measurement results for NC (b) Measurement results for DLC 3

Fig. 11. Traction measurement results (engine oil)

The trend is more clearly elucidated by converting the x-axis of the graphs obtained through traction measurement to slip velocity (rotation speed × slip ratio) and drawing graphs by plotting the ratio of the friction coefficient of DLC 3 to that of NC (friction coefficient of DLC 3 ÷ friction coefficient of NC) obtained under different conditions (Fig. 12). In either lubricating oil, the friction coefficient ratio decreased with increasing slip velocity. In engine oil, the friction coefficient ratio was less than 1 in almost all regions. These results reveal that the friction reduction effect of DLC coating increases with increasing slip velocity, and that the effect is more prevalent with the lower viscosity of the lubricating oil.

According to these results, it is highly likely that the friction-reduction effect of DLC increases with lower oil viscosity, higher rotation speed, and higher slip ratio.



(a) Measurement results in Machine oil (b) Measurement results in Engine oil

Fig. 12. Change in the friction coefficient ratio in response to slip velocity

5. Conclusion

Coating of hydrogen-free DLC onto gears proved effective in improving their durability (pitting fatigue life). In particular, hydrogen-free DLC with a lower Young's modulus than that of the substrate was effective.

Additionally, sliding testing in rolling-sliding environments revealed that the friction reduction effect achieved by coating hydrogen-free DLC increases with lower oil viscosity, higher rotation speed, and higher slip ratio.

Technical Terms

*1 DLC: Abbreviation for diamond-like carbon. DLC is a generic term for amorphous thin films whose main component is carbon.

*2 ta-C: Abbreviation for tetrahedral amorphous carbon. DLC films known as "ta-C" contain a high percentage of diamond structure and no hydrogen.

*3 a-C: Abbreviation for amorphous carbon. DLC films known as "a-C" contain a high percentage of graphite structure and no hydrogen.

*4 Pitting: Damage characterized by the development of pits due to fatigue at very small irregularities on tooth faces subjected to repeated high stress.

*5 Maximum Hertzian contact stress: When the contact surfaces of two objects under loading in the vertical direction undergo elastic deformation, the bearing stress on the contact surfaces is termed "Hertzian contact stress." The maximum Hertzian contact stress refers to the bearing stress at the point at which the highest Hertzian contact stress occurs.

*6 ATF oil: Abbreviation for "automatic transmission fluid." ATF oil refers to oil used in automotive transmissions.

References

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