電気自動車用低粘度潤滑環境における DLC 膜のトライボロジー特性に関する研究

Study of tribological properties of DLC coatings in low viscosity lubrication environments for electric vehicles

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1. Introduction

The rapid development and adoption of electric vehicles (EVs) are being driven by increasingly stringent emission regulations aimed at reducing air pollution. However, new challenges have emerged in EV powertrains due to the electrical environment, including issues such as spark tracks, pitting, and welding in bearings and gears within reducers caused by discharge voltage and current from the drive motor shaft. Furthermore, the use of low-viscosity lubricants to improve fuel efficiency has accelerated gear wear resulted in reduced oil film thickness, leading to increased contact pressure. To address these challenges, bearings and gears in EV drivetrains must possess high electrical insulation (over 1×10^{6} Ω). Diamond-like Carbon (DLC) coatings are one of the few promising materials that can simultaneously satisfy insulation, friction, and wear depending on sp^2, sp^3, and hydrogen, and are categorized as amorphus-carbon:hydrogen (a-C:H) with high sp^2 and hydrogen content, tetrahedral amorphous-carbon (ta-C) with high sp^3 content, and tetrahedral amorphous-carbon:hydrohen (ta-C:H) with high sp^3 and hydrogen content. superior wear resistance, and low friction ($\mu < 0.1$). DLC coatings, which can be deposited as thin as a few micrometers, offer the potential to meet these stringent requirements. DLCs provide excellent electrical insulation, wear resistance, and low friction, even in boundary lubrication. These coatings are particularly effective in maintaining low friction characteristics during high-speed rotation and under high-temperature conditions where oil film thickness is compromised. Given that EV drive motors operate under various conditions, including stopping, accelerating, and decelerating, it is crucial to select a DLC coating that is optimized for the varying speeds and temperature change encountered in these environments. Therefore, in this study, to find the relationship between elastic modulus and electrical resistance, ta-C (highest elastic modulus, medium electrical resistance), a-C:H (lowest elastic modulus, lowest electrical resistance), and ta-C:H (medium elastic modulus, highest resistance), excluding a-C whose electrical resistance does not satisfy over 1×10^{6} Ω, were selected to select the most suitable DLC coatings for the electric vehicle motor bearing environment. Stribeck curves measured by varying (1) speed and (2) oil viscosity through temperature control in a potentialized environment to realize the actual electric vehicle driving environment.

2. Experimental details

The specimens were prepared by performing Ar ion etching with a linear ion source (LIS) on the surface of SUJ2 bearing steel to remove surface oxide films and contaminants. A titanium interlayer, 200 nm thick, was then deposited using an unbalanced magnetron sputter (UBMS). Subsequently, the ta-C coating was fabricated to a thickness of 1 µm using a filtered cathodic vacuum arc (FCVA) technique. For the ta-C:H coating, the same FCVA technique was employed with the addition of 100 sccm of flowing H_2. a-C:H coating was deposited using LIS with flowing C_2H_2 gas for deposition. Tribological testing was conducted using a ball-on-disk type tribometer with a normal force of 5 N, and SUJ2 ball with a diameter of 9.0 mm was utilized as their counterpart. The lubricant used in the tests was a commercially available synthetic automatic transmission fluid (HYUNDAI MDF & DCTF 70W, 30 mL). The experimental conditions for evaluating the friction behavior, considering dielectric breakdown voltage and oil viscosity, are detailed in Table 1.

Table 1 Detailed conditions for a ball-on-disk tribotesting

Test (1): Insulation breakdown voltage		**Test (2): Friction behavior by oil viscosity**			
Track radius	7 mm	**Track radius**	7 mm		
Temperature	100℃	**Temperature**	23℃ (R.T)	60℃	100℃
Speed (RPM)	50	**Speed (RPM)**	50	50	50
Discharge Voltage	5-30 V		100	100	100
			300	300	300
			500	500	500

3. Results and discussion

For test (1) the dielectric breakdown voltage measurements of the DLC coatings are shown in Fig. 1. Among the tested coatings, ta-C, which showed the highest mechanical properties (E = 600 GPa), exhibited a dielectric breakdown voltage of 20 V. On the other hand, among ta-C:H and a-C:H with similar mechanical properties (E = 250 GPa), the dielectric breakdown occurred at 15 V for the ta-C:H coating with the highest surface electrical resistance, and at 10 V for the a-C:H coating with the lowest surface electrical resistance. These results confirm that the surface electrical resistance affects a little dielectric breakdown. For test (2) the tribological behavior of the ta-C, ta-C:H, and a-C:H coatings lubricated with an applied voltage of 5 V is shown in the Stribeck curves in Fig. 2. At low speeds where the Hersey number is less than 1, the friction coefficients of all DLC coatings were similar. However, significant differences were observed at high-speed conditions characterized by higher Hersey numbers. The a-C:H coating showed the lowest coefficient of friction (μ: 0.02), followed by ta-C:H (μ: 0.04) and ta-C (μ: 0.06). These results indicate that a-C:H provides superior tribological performance under low viscosity lubrication conditions and electrical resistance.

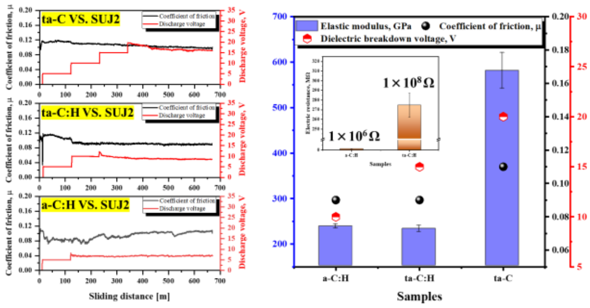

Fig. 1 Dielectric breakdown voltage and mechanical properties of DLC coatings.

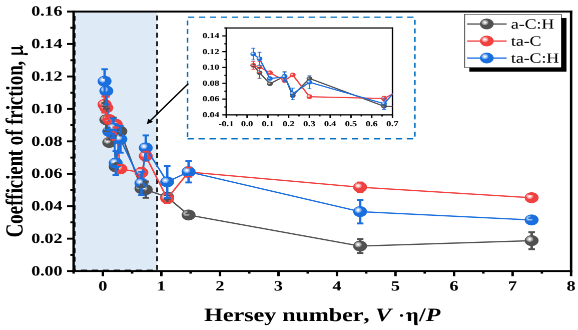

Fig. 2 Stribeck curve of DLC coatings

4. Conclusions

This study tried to identify the optimal DLC coating for electric vehicle drives that offers superior electrical insulation, low friction, and wear resistance in electrical and low-viscosity lubrication. The findings indicate that ta-C with higher mechanical properties tend to exhibit improved dielectric breakdown voltage. Among ta-C:H and a-C:H with similar mechanical properties, enhancing surface electrical resistance is an effective to further increase dielectric breakdown voltage. Additionally, it was observed that ta-C:H and a-C:H coatings, which contain hydrogen, demonstrate lower friction characteristics in low-viscosity environments. However, further research is required to fully understand the impact of hydrogen on the electrical performance and friction behavior of DLC coatings in such environments, as well as to explore methods for improving dielectric breakdown voltage.

Acknowledgments

This study was supported by the Fundamental Research Program (grant number: PNK 9920) of the Korea Institute of Materials Science (KIMS).