

Friction Behavior of Diamond-Like Carbon Coated Ball Joint: Approach to Improving Vehicle Handling and Ride-Comfort

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ABSTRACT

Research to respond to demands for improving usability of passenger vehicles has played important roles. Some aspects can be attributed to friction behavior of the steering and suspension components. In this study, we focus on an approach to improve handling, steering feel and ride-comfort of a vehicle by applying the appropriate friction behavior to tie-rod end ball joint. To control not only friction coefficient but also static-kinetic transient behavior, we investigate the potential use of diamond-like carbon (DLC) coatings. Different DLC coatings varied widely in hydrogen content, mechanical properties and micro-surface roughness are applied to the ball studs. Friction behavior corresponds to material characteristics and surface roughness of DLC. The "polymer-like" DLC with higher hydrogen tend to show higher kinetic friction and remarkable stick-slip behavior at the static-kinetic transient period, whereas the "graphite-like" DLC with lower hydrogen show lower kinetic friction and smooth transient behavior. From dynamic evaluation results of actual vehicle, the "graphite-like" DLC gives an appropriate friction behavior for the ball joint, leading to an improved steering feel, vehicle stability and ride-comfort. In contrast, the excessive friction causes a sticky steering feel and an increased harshness with high frequency vibration. We discuss the effectiveness in friction behavior of DLC-coated ball joints depending on the DLC coating properties, with either positive or negative effects found for vehicle handling and ride-comfort.

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INTRODUCTION

Recently, tribological investigations on mechanical components have been directed toward responding to the demands for friction reduction and long-term durability to improve fuel economy and to address environmental issues [1, 2]. In another aspect, tribology also plays important roles in a tactile property, feeling and usability of the products such as the smart phones, touch panels, cosmetics, hand creams and clothes [3, 4]. Some aspects of handling, steering feel and ride-comfort of a passenger vehicle can be attributed to the tribological performance of the steering and suspension components.

Ball joint is the important component which can realize the vertical motion of suspension systems and the rotational motion of steering systems at the same time. Ball joints have been required the improved tribological performance and reliability in automobile steering and suspension systems [5]. It is known that the component which has a high friction force contributes to inhibit vibration and fluttering of the steering and suspension systems. A pre-load of ball joint can be increased by tightening the ball stud in its assembling process. This can suppress a fluttering, vibration and shimmy in a running vehicle to a certain extent. However the high pre-load of ball joint increases the torque at the initiation of motion, causing a heavy handling without smoothness and unpleasant steering feel. Thus, both the low friction for smooth sliding initiation and the high friction for inhibiting vibration are required. It is essential to understand the

friction behavior of ball joints not only in terms of low- or high-friction coefficients, but also in terms of the static-kinetic transient motion [6].

One approach to obtaining the desired friction behavior is the improvement of lubricants and greases. The compositions of lubricants for ball joints have been proposed [7]. It is reported that the composition containing a base-oil or a wax mixed with an amidoamine compound and a fatty acid salt exhibits excellently low friction during low speed driving, but exhibit high friction during high speed driving [8]. This lubricant has the effective frequency characteristic for inhibiting fluttering, but cannot maintain the desired property in higher and lower temperature ranges, causing increased friction.

Another approach to controlling friction behavior is the potential use of surface treatment and coating techniques submitted to boundary lubrication. It is reported that a technique for forming a magnetite layer on the surface of ball stud [9]. It can achieve a great wear resistance and corrosion resistance. However, the magnetite layer provides no significant difference from usual steel in friction behavior, due to its ferrous characteristics. Modern lubricants and greases are mainly developed for ferrous materials. These compositions act on the sliding steel surface effectively, so that the friction behavior is principally dominated by characteristics of lubricants.

Diamond-like carbon (DLC) coatings are well-known for their outstanding sliding performances as well as high hardness and wear resistance [10]. The “non-ferrous” carbon material surfaces are generally inactive to lubricants. On the other hand, hydrogenated DLC coatings have amorphous carbon bond structure with hydrogen, so that their chemical and physical properties can be varied diversely. Thus, DLC coatings have a possibility to control the boundary friction behaviors and to provide the frequency characteristics widely depending on the motion condition. However, the interaction between DLC coatings and lubricants is complicated and not clear in detail.

In this study, we focus on an approach to improve the handling, steering feel and ride-comfort of a vehicle by applying the appropriate friction behavior to the tie-rod end ball joint (as shown in Fig. 1). In order to investigate the relation between DLC coatings and friction behavior of ball joints, the different DLC coatings varying widely in hydrogen content, mechanical properties and micro-surface roughness were applied to the ball studs. The chemical analyses on the sliding surfaces are employed to gain an understanding of the boundary film compositions derived from lubricant. We discuss the effectiveness in friction behavior of DLC-coated ball joints depending on the DLC coating properties, with either positive or negative effects found for vehicle handling and ride-comfort.

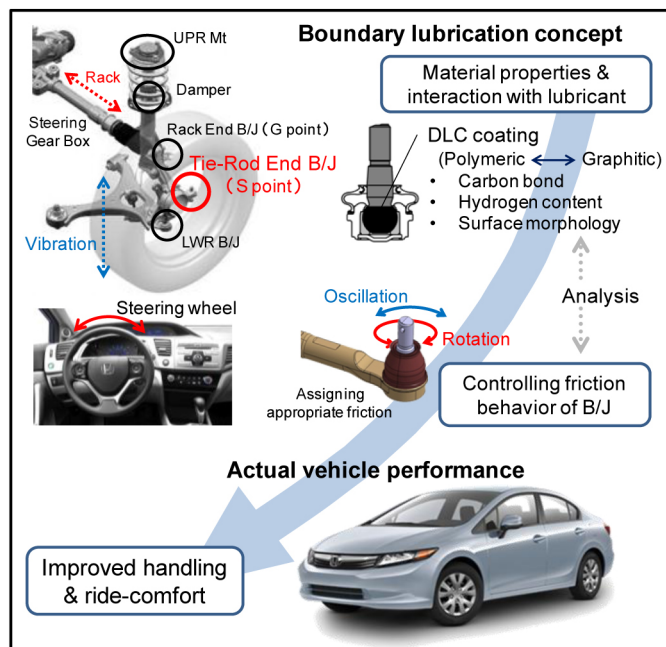


Figure 1. Graphical image of research concept in this paper: controlling friction behavior of tie-rod end ball joint by DLC coating application to improve handling and ride-comfort.

EXPERIMENTAL DETAILS

Ball Joints and DLC Coatings

Figure 2 shows the structure of a tie-rod end ball joint. Ball stud was coupled to a resin bearing sheet with lubricant. They were pushed into the tie-rod end housing and plugged with the steel plates. The ball stud was made of steel (SAE 1536B). The diameter of the ball

was 20 mm. The resin sheet material was polyacetal (POM: polyoxymethylene, M90-44, OILES Co.). Lubricant (CRANOC COMPOUND FL, JX Nippon Oil & Energy Co.) was applied for the lubrication between the ball stud and resin sheet. The ball stud can rotate freely and can swing within the limit of its rocking angle to change its joint angle between the two members for allowing universal motion in two planes at the same time.

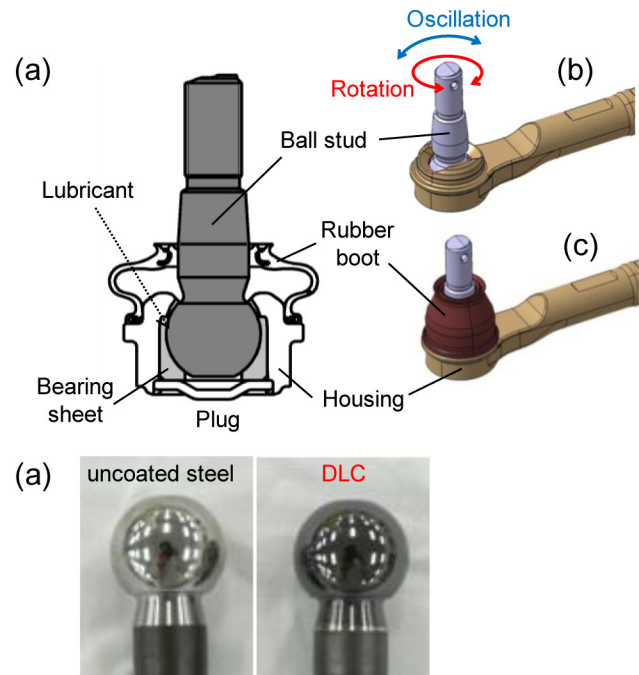


Figure 2. Schematic illustrations of (a) cross section of tie-rod end ball joint, (b) tie-rod end ball joint without rubber boot, and (c) tie-rod end ball joint with rubber boot.

Hydrogenated diamond-like carbon (DLC) coatings were deposited on the spherical surface section of the ball studs using a plasma assisted chemical vapor deposition (PACVD) method, as shown in Fig. 3. The different DLC coatings were obtained by varying the precursor gas and deposition conditions. These DLC coatings varied in carbon bonding structure, hydrogen content, mechanical property and microscopic surface morphology. The deposition was conducted under 0.5 Pa gas pressure, using acetylene (C_2H_2) or methane (CH_4) as a carbon source. The substrate bias voltage was varied within a range of 50-500 V.

Additionally, in order to obtain different surface morphologies, the intermediate layer of sputtered titanium (Ti) was deposited before the DLC top layer using a magnetron sputtering method during the deposition process (in Fig. 3). The microscopic surface roughness of DLC coatings is principally determined by the substrate roughness and the DLC growth process [11]. Ti can be deposited at a higher deposition rate than DLC, and the Ti intermediate layer generally gives a rough surface. The DLC top layer traces the Ti layer morphology, so that the microscopic roughness was controlled by varying the Ti layer thickness and the DLC deposition condition. The coated surfaces are the so-called as-deposited, which did not have any surface finishing treatment.

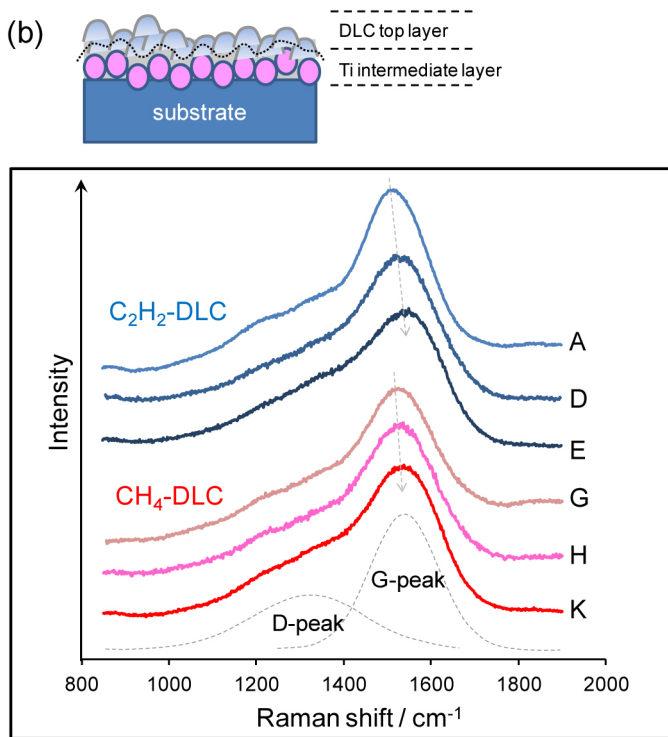


Figure 3. (a) Photograph of uncoated steel ball stud and DLC-coated ball stud, and (b) schematic illustration of layer structure of the DLC coating.

Characterization of DLC Coatings

Table 1 shows the characteristics of the DLC coatings. Carbon bonding structures of the DLC coatings were characterized by Raman spectroscopy. Raman is widely used as a non-destructive method to characterize the structural quality of carbon materials; diamond, graphite, and so on.

Table 1. Characteristics of the DLC coatings.

Sample No.	Deposition			Cont.	Raman		AFM		Nano-indentation	
	Gas	Bias	Ti thickness	Hydrogen	G-peak	ID/IG	Sq	Sdr	Hardness	E-Modulus
	-	-	[μm]	[at.%]	[cm⁻¹]	-	[nm]	[nm]	[GPa]	[GPa]
A	C₂H₂	Low	0.25	37	1523	0.36	21	1.036	7.8	57.2
B	C₂H₂	Low	0.5	37	1521	0.34	33	1.062	8.4	63.8
C	C₂H₂	Mid	0.5	34	1529	0.41	30	1.038	11.8	105
D	C₂H₂	Mid	none	26	1539	0.47	11	1.017	17.9	149
E	C₂H₂	High	none	21	1556	0.68	13	1.012	29.2	248
F	C₂H₂	High	0.5	21	1552	0.53	25	1.029	32	271
G	CH₄	Low	0.25	37	1530	0.39	14	1.017	14.5	110
H	CH₄	Mid	0.25	32	1535	0.43	13	1.010	22.5	172
I	CH₄	Mid	0.5	32	1535	0.42	18	1.010	26.2	200
J	CH₄	Mid	none	-	1543	0.43	6.4	1.001	24.7	184
K	CH₄	High	none	-	1547	0.56	7.3	1.002	18.9	141

Figure 4 shows the Raman spectra of the DLC coatings. They were obtained within the range of 850-1900 cm⁻¹ by the laser irradiation (Nd:YAG, 532nm) using LabRAM ARAMIS (HORIBA Jobin Yvon S.A.S.). The Raman parameters were obtained by the peak decomposition treatment of the Raman spectra. The spectra line was fitted with a Gaussian-Lorentzian line for the so-called G and D peaks, which lie at around 1500-1600 cm⁻¹ and around 1350cm⁻¹

respectively. The G-peak is due to the bond stretching of all pairs of sp² atoms in both six-fold rings and carbon chains, and the D-peak is due to the breathing modes of sp² atoms in rings [10, 12, 13]. The G-peak position corresponds to the sp² configuration and the sp³ fraction with hydrogen, in hydrogenated DLC. The other important parameter is the intensity ratio of the D and G peaks, I(D)/I(G). In amorphous carbons, I(D)/I(G) is measure of the size of the sp² phase organized in rings [10, 12, 13].

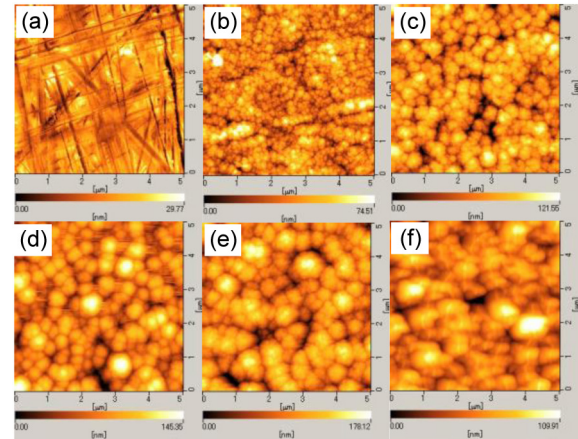


Figure 4. Raman spectra of the DLC coatings.

The hydrogen and carbon content of the DLC coatings were also characterized by hydrogen forward scattering spectrometry (HFS) and Rutherford backscattering spectrometry (RBS) using Pelletron 3SDH (National Electrostatics Corporation). The hardness and elastic modulus of the DLC coatings were measured by means of a nano-indentation method. The measurements were performed based on ISO14577 using Nano Indenter XP (MTS Systems Corporation) to estimate the nano-indentation hardness and the elastic modulus. The microscopic surface morphology of the DLC coatings was observed by means of atomic force microscopy (AFM) using SPI4000 NanoNavi/E-sweep (SII Nano Technology Inc.). The surface parameters of the root mean square height (Sq) and the surface developed area (Sdr) were estimated based on ISO 25178. Figure 5 shows AFM images of the DLC coating surfaces. The DLC coating surfaces displayed small mound structures. The size and shape of the mound structures seemed to depend on the Ti intermediate layer and the DLC growth process. It was observed that the thicker the Ti intermediate layer, the larger the mound size, leading to the greater roughness.

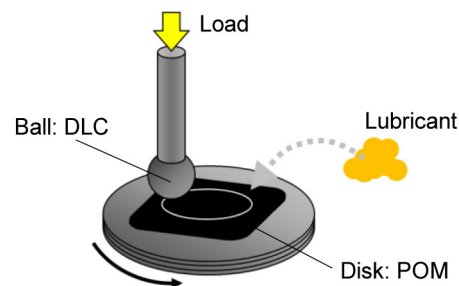


Figure 5. AFM images of (a) uncoated steel and the DLC coating surfaces; (b) sample-D without Ti intermediate layer, (c) sample-A with 0.25 μm Ti layer, and (d) sample-F, (e) sample-C and (f) sample-I with 0.5 μm Ti layer.