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Frictional properties of diamond and fullerene nanoparticles sprayed by a high-velocity argon gas on stainless steel substrate

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Abstract

Lubricating abilities of diamond nanoparticles with size between 50 nm and 200 nm were studied in vacuum and in air to clarify the effective use of diamond fine powders for tribological purposes. Spraying of powders with a high-velocity argon gas jet was performed to form deposits on stainless steel (SUS304) substrates. For sliding in vacuum against SiC and Al_2O_3 balls under a 0.5 N applied load and 3.5 mm/s sliding speed, the deposits of microcrystalline diamond powders with a mean particle size of 50 nm and detonation nanodiamond with a mean aggregate size of around 75 nm demonstrated friction coefficients of less than 0.01 and 0.03, respectively, and ball wear rates of less than $2 \cdot 10^{-6}$ mm^3/(Nm). This means that diamond fine powders smaller than 100 nm can be considered as good solid lubricants in vacuum, because they demonstrate not only a low friction coefficient, but also wear rate of SiC ball lower than non-lubricated SUS304 does. A C_{60} deposit, formed by the same method on the SUS304, was readily scratched from the substrate in vacuum; however, under open-air conditions, a friction coefficient of around 0.1 and a SiC ball wear rate of about $2 \cdot 10^{-6}$ mm^3/(Nm) were observed. This fact calls attention to the influence of the deposition method on C_{60} frictional properties.

Keywords: Diamond crystal; Fullerenes; Nanoparticles; Friction

1. Introduction

The search for new low-frictional materials and the improvement of the tribological characteristics of actual materials is a topical problem. Detonation nanodiamond (ND), owing to its advantageous uniform grain size of about 5 nm, nearly round shape and crystalline structure, has shown promise as an effective lubricating additive to various materials and composites [1–3]. The recently reported high lubricating ability of onion-like carbon (OLC) synthesized by heat treatment of ND has been believed to come from the uniform and round shape of the OLC grains [4]. However, it is known that ND grains in both powder and suspended forms exist as aggregates with fractal structures and the size of such aggregates may be many times larger than the grain size [5]. It is expected that tribological properties of ND can be strongly influenced by the size and structure of those aggregates. Therefore, it is necessary to gain a better understanding of the behavior of ND aggregates compared with non-aggregated diamond powders of equivalent size in order to establish a microscopic view of the lubricating mechanism of ND and to clarify the effective use of ND and other diamond fine powders for tribological purposes.

In our previous paper [6], we showed that gas sprayed ND powders and microcrystalline diamond powders with an average particle size of 50 nm gave a very low coefficient of friction in dry friction tests, comparable with that of polished chemical-vapor deposited (CVD) diamond film, for sliding against SiC in vacuum under a 0.5 N load and 3.5 mm/s sliding

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speed. We found that the lubricating property of ND was dominated by the average size of ND aggregates rather than by the features of individual grains. Diamond powders with a particle/aggregate size of less than 100 nm formed a smooth, compact layer in the sliding track, thus creating very low friction in vacuum. Based on those results, in this paper we continue to discuss the frictional characteristics of ND powder and microcrystalline diamond powders of various particle sizes. More precise friction measurement results, wear rates in particular, were obtained by performing additional experiments with longer test times. The roughness of the compressed powder layers formed in a contact zone during the sliding test was studied by atomic force microscopy (AFM). The tribochemical processes, which take place under air conditions, were investigated using two different counter-body materials (SiC and Al_2O_3). For the sake of comparison the friction test on fullerene (C_{60}) powder was carried out.

2. Experimental methods

Table 1 shows the specifications of materials used in this work. Deposits of powder samples were fabricated by a simple spray deposition technique, as shown in Fig. 1. The powder, about 0.1 g in weight, was charged with pressurized argon in a reservoir at room temperature. When the diaphragm was ruptured, the powder was introduced into a vacuum tube, resulting in the formation of a powder jet that was sprayed on a substrate located in a vacuum chamber. The peak velocity of the argon gas was calculated to be about 500 m/s and the final powder velocity was assumed to be between 150 and 500 m/s depending on the powder size [7]. The obtained deposits were typically approximately 1 μm in thickness, and both the particle–particle and the particle–substrate bindings were weak. The deposits were detached from the substrate when they were rubbed with a finger. It is supposed that the force between the particles and the substrate is a van der Waals force with a dispersive nature.

The lubricating abilities of deposits were observed by using a ball-on-disk friction tester (Rhesca, Friction Player) in ambient air (RH = 12–26%) and high vacuum, typically under less than 1×10^{-3} Pa pressure. To obtain a reference on the lubricating ability of diamond film, friction measurements were also conducted under the same experimental conditions on a polished polycrystalline diamond film fabricated by CVD on silicon.

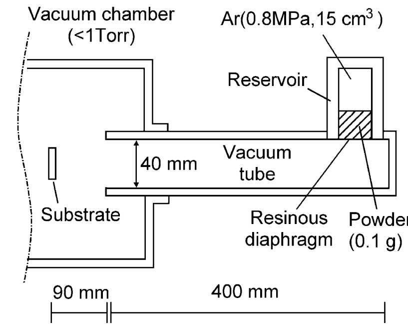

Fig. 1. Schematic illustration of the spray deposition technique.

Friction measurements were carried out at a sliding speed of 3.5 mm/s with a load of 0.5 N. Typically, the total time of friction measurement was 1200 s, which corresponded to a total sliding distance of 4.2 m. The total number of revolutions of the sliding track was between 120 and 400, depending on the diameter of the path. After each friction measurement, the surface of the powder deposits covered by a 10 nm Pt–Pd layer was observed by scanning electron microscopy (SEM, Hitachi S5000) and AFM (Seiko Instruments Nanopics1000). The diameters of wear scars on the balls were measured with an optical microscope to calculate the specific wear rates Ws of the balls, defined as $Ws = V/(W\cdot L)$, where V, W and L were a loss in volume, the applied load and the sliding distance, respectively, and the volume loss of the ball was calculated from the observed diameter of the wear scar on the ball.

3. Results

Typical friction curves measured in vacuum for the fine diamond and C_{60} deposits and the CVD diamond film

Table 1
Specifications of materials

	Detonation nanodiamond (ND)	ca. 75 nm[a]	Sinta, Belarus, UDD-DP
Lubricant	Mechanically crushed single-crystal diamond (MD50, MD100, MD200)	MD50/ca. 50 nm MD100/ca. 100 nm MD200/ca. 200 nm	Tomei Diamond, Japan, MD50, 100, 200
	C_{60} fullerene	50–200 μm[a]	Fullerene Technologies, Russia, OM-9
	CVD diamond film on silicon	Thickness > 12 μm[b]	Sumitomo Electric, Japan
Ball	Sintered SiC	Diameter 4.76 mm	Showa Denko, Japan, C-TB
	Sintered Al_2O_3	Diameter 4.76 mm	Koyo Seiko, Japan, A99
Substrate	SUS304	15 × 15 × 2 mm[b]	

[a] Size of aggregate.
[b] Polished to Ra < 10 nm in roughness.