Very low friction for diamond sliding on diamond in water

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This letter reports the lowest coefficient of friction measured for diamond sliding on diamond. When a natural diamond stylus with a spherical tip about 50 μm in diameter slides on a polished polycrystalline chemically vapor deposited diamond film in water at a speed of 0.05 mm/s under a load of 50 g, the coefficient of friction falls to $\sim$0.001. This clearly shows the effectiveness of water for lubricating diamond sliding on diamond.

The recent rapid development of large area and high rate chemical vapor deposition (CVD) processes for diamond films has stimulated broad applications for diamond.[1] Diamond sliding on diamond is known to have a low coefficient of friction of between 0.05 and 0.15 in air, but a much higher coefficient of friction of between 0.5 and 1 in a vacuum.[2-4] The formation of strong carbon-carbon bonds across the clean interface formed between sliding diamond surfaces in a vacuum is believed to be the cause of the high coefficient of friction. Diamond surfaces can be covered with chemisorbed hydrogen and oxygen as well as physically adsorbed water molecules. The frictional force caused by adhesion between two diamonds sliding against each other in air is thus lower than that in a vacuum. This letter reports a coefficient of friction as low as 0.001 for diamond sliding slowly on diamond in water under a low load.

Coefficients of friction were measured using a reciprocating type of tribometer consisting of a balanced metal arm and a moving stage (Fig. 1).[5] A diamond stylus with a $\langle 110\rangle$ axis and a spherical tip about 50 μm in diameter was vertically mounted at one end of the metal arm. This arm was suspended by three steel wires that held it rigidly in the lateral direction while allowing it to move up and down freely. The CVD diamond film was placed on the specimen stage, which was moved horizontally relative to the stylus by a screw micrometer driven by a computer-controlled stepper motor. The normal force was applied by placing a suitable dead weight above the stylus. The frictional force was measured by means of strain gauges mounted on the steel strips which connected the stylus holder to the metal arm. The strain gauges formed a Wheatstone bridge which is connected to a Philips PR9307 carrier frequency bridge amplifier that produced direct current (dc) signals for an analog-to-digital converter. The strain gauges were calibrated by applying loads in the horizontal direction to establish a curve of output voltage versus lateral force. Interpolation and extrapolation were then used to calculate frictional forces by comparing the output voltage during sliding to the output voltage corresponding to the zero frictional force that was set before each experiment started. The residual force acting on the strain gauges due to imperfect leveling of the sliding stage was canceled by the reciprocative sliding and a computer code used for data processing. The polycrystalline diamond film, which was about 20 μm thick, was deposited on a sintered silicon nitride substrate using the hot filament CVD technique and consisted predominantly of {100} oriented grains.[6] This film was rough polished using a diamond wheel and then finished on a cast-iron diamond scaife, resulting in a local surface roughness of about 10 nm, peak-to-valley, measured by an Alpha step profilometer. The diamond stylus and the CVD diamond film were cleaned by acetone followed by methanol and then blown dry by nitrogen before each experiment.

Shown in Fig. 2 are the coefficients of friction measured at a sliding speed of 0.2 mm s^{-1} and a load of 100 g. When water was applied to the area of contact at room temperature, the coefficient of friction decreased to about 0.01. After the water was blown away, the coefficient of friction increased back to its usual value in air of 0.04. These coefficients of friction are similar to those reported in Ref. 5 for the same diamond stylus sliding on a natural diamond. When the sliding speed was held constant at 0.2 mm s^{-1}, the coefficient of friction did not change significantly in either water or air when the load was changed from 50 to 200 g. With a load greater than 100 g, the coefficient of friction did not change much when the sliding speed was varied from 0.05 to 0.3 mm s^{-1}.

The adsorption of water on diamond surfaces is crucial to its effectiveness as a lubricant in the present experiments. After water was applied to the diamond surfaces, the coefficient of friction decreased gradually over a few traversals, during which the surface of the diamond was

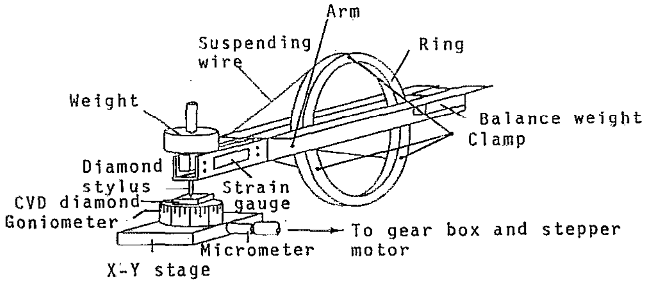

FIG. 1. Schematic diagram of the reciprocating type of tribometer used for this work.

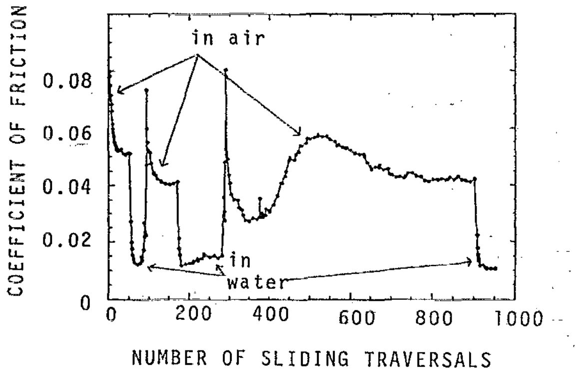

FIG. 2. Coefficients of friction for a diamond stylus sliding on a polished CVD diamond film at 0.2 mm s^{-1} under a load of 100 g. The diamond stylus had a tip diameter of 50 μm. The CVD diamond film was polished to a roughness of about 5 nm. Distilled water was alternately applied to the diamond surfaces and blown away by a flow of nitrogen.

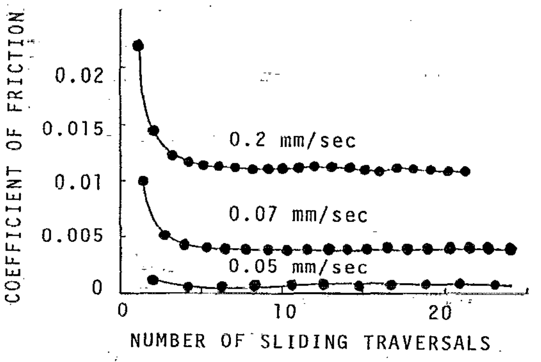

FIG. 4. Coefficient of friction for the same diamond stylus sliding on a similarly polished CVD diamond film in water under a load of 50 g at different sliding speeds.

modified. After nitrogen was used to blow most of the water away from the sliding surfaces, it took a few traversals to remove the remaining film and to replace the chemisorbed and physically adsorbed layers on the surfaces of the stylus and the film with those which form in air. The coefficient of friction then rose to higher values, as shown in Fig. 2. These experimental results indicate that, although some effect of surface roughness[7] cannot be completely ruled out, adhesion does play a more important role in determining the coefficient of friction for diamond sliding on diamond in air. The resultant small coefficient of friction ($\sim$0.01) might be caused by residual adhesion due to incomplete lubrication, by the finite roughness of the sliding surfaces, or by a combination of both mechanisms.[8] If the lubrication is made more complete and the surface made smoother, the friction of coefficient may decrease further.

Shown in Fig. 3 are the coefficients of friction measured in water and in air at a sliding speed of 0.05 mm s^{-1} under a load of 50 g. Several alternate sliding in air and water were performed before the experiments were run to collect the data shown in Fig. 3. When sliding in air, the coefficient of friction measured at 0.05 mm s^{-1} was about the same as that measured at 0.2 mm s^{-1}. When water was applied to the area of contact during sliding at 0.05 mm s^{-1} under a load of 50 g, the coefficient of friction decreased to a very low value of around 0.001, which is one order of magnitude lower than that measured under otherwise similar conditions at a sliding speed of 0.2 mm s^{-1}. The effectiveness of water in lowering the coefficient of friction from about 0.06 in air to 0.001 was further demonstrated by alternately applying water to the area of contact and blowing it away with a stream of nitrogen without otherwise interrupting the experiment. The coefficient of friction for diamond sliding on diamond in air thus served to calibrate the measurement of the very low coefficient of friction obtained when water was applied.

The very low coefficient of friction increased when the sliding speed was increased from 0.05 to 0.2 mm s^{-1} with all other conditions kept the same (Fig. 4). At a constant sliding speed of 0.05 mm s^{-1}, the coefficient of friction in water also increased when the load was increased above 50 g (Fig. 5). A comparably low coefficient of friction ($\approx$0.002) was previously reported for silicon nitride sliding against itself in water at a speed of three orders of magnitude higher than the present case. It was attributed to the hydrodynamic lubrication made possible by the dissolution of silicon nitride in water and the absence of wear

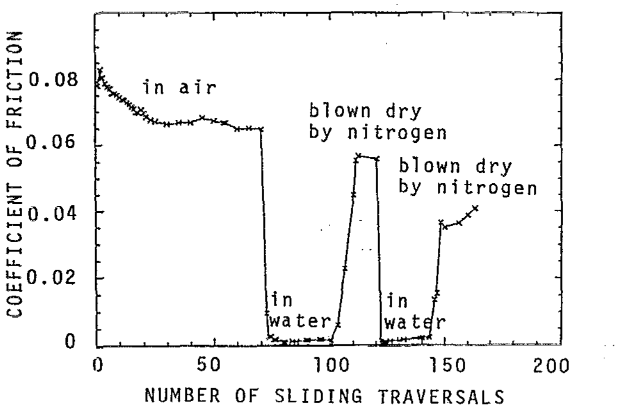

FIG. 3. Coefficient of friction at a sliding speed of 0.05 mm s^{-1} under a load of 50 g. The same diamond stylus and diamond film as the ones for Fig. 2 were used.

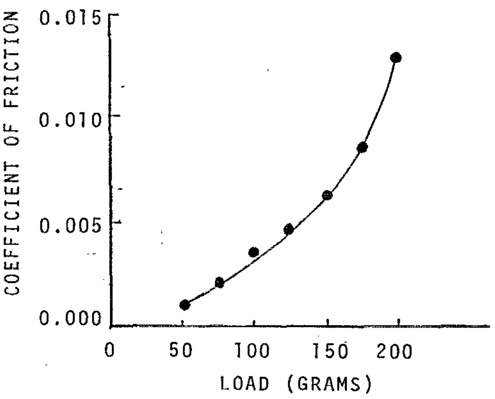

FIG. 5. Coefficient of friction for the same diamond stylus sliding on a similarly polished CVD diamond film in water at a sliding speed of 0.05 mm/s under different loads.

particles. The coefficient of friction for silicon nitride sliding against itself increased with decreasing sliding speed and reached a value of 0.7 at a speed of 2 mm s^{-1}.[9] That is in contrast to the decreasing coefficient of friction with decreasing sliding speed down to 0.05 mm s^{-1} for our case. Therefore, the hydrodynamic lubrication does not play a role in our experiments. The very low coefficient of friction of ~0.001 for diamond sliding on diamond is most likely caused by the almost complete elimination of adhesion. When diamond asperities slide against a diamond surface passivated by water, it may partially damage the passivation layer. If this area is not recovered, it will cause a high coefficient of friction when the next diamond asperity reaches the nonpassivated diamond surface. When the sliding speed is low, it gives the scratched diamond surface sufficient time to again become passivated by water. When the load is lower, the extent to which the surface passivation is damaged by the sliding motion is less. The combination of a low load and a slow sliding speed makes it more possible to effectively remove adhesion between opposed diamond surfaces leading to a very low coefficient of friction for diamond sliding on diamond in water.

In summary, a coefficient of friction as low as 0.001 has been measured for diamond sliding on a polished polycrystalline CVD diamond film in water at a sliding speed of 0.05 mm s^{-1} under a load of 50 g. The excellent lubricating effect of water on reducing adhesion between diamond surfaces has been clearly demonstrated. More research is needed to further confirm the exact mechanism responsible for this very low coefficient of friction.

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