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SUPERLUBRICITY IN CARBON FILMS*

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This paper describes a new carbon film that afford superlubricity (i.e, friction coefficients of 0.001-0.005) and superlow wear rates (i.e., $10^{-11} - 10^{-10}$ mm^3/N.m) to sliding metallic and ceramic surfaces, when tested in inert test environments. The wear life of these films are more than 1000 km even under very high contact pressures (i.e., 1-3 GPa) and at a wide range of sliding velocities (i.e., 0.1 to 2 m/s). They are produced in a plasma enhanced chemical vapor deposition system at room temperature using highly hydrogenated gas discharge plasmas. Extensive research has shown that films grown in highly hydrogenated gas discharge plasmas (i.e., hydrogen-to-carbon ratio of 6 and above) provide superlow friction and wear coefficients. In full paper, specific conditions under which superlubricity can be achieved in carbon films will be discussed.and a mechanistic model will be proposed to explain the superlubricity of new carbon films.

Keywords: Superlubricity, Diamondlike Carbon, Lubrication Mechanisms, Plasma Aisted Dposition.

1. INTRODUCTION

Diamondlike carbon (DLC) films have attracted a great deal of interest in recent years mainly because of their unique properties suitable for a wide range of industrial applications [1-3]. In addition to their excellent chemical inertness and high resistance to corrosion, these films can provide some of the lowest friction coefficients and wear rates with or without any type of solid and/or liquid lubrication. Some of these coatings are also super hard and strong making them very suitable for applications involving abrasion and/or scratching.

Structurally, DLC films are amorphous and made of sp^2- and sp^3-bonded carbon atoms. Depending on the deposition process and carbon sources, they may also contain large amounts of hydrogen in their microstructures. They may be alloyed with other elements (e.g., nitrogen, fluorine, oxygen, silicon, tungsten, titanium, and niobium) to achieve higher thermal and/or electrical conductivity, better transparency, or different levels of dielectric properties. They can be derived from all kinds of carbon based materials and hydrocarbon gases and deposited on a wide range of metallic, ceramics, and polymeric materials. Their synthesis is rather easy and can be achieved even at room or subzero temperatures. Applications possibilities for these coatings are many and may vary from numerous tribological systems to a variety of microelectronics and optical devices.

Systematic studies on diamond, DLC, and other related materials over the last decade or so in our laboratory [4-18] have led to the discovery of an amorphous carbon film that now provides friction and wear coefficients of 0.001 and 10^{-11} mm^3/N.m, respectively when tested in dry nitrogen or argon. Specifically, we have found that when we purposely add hydrogen (up to 90%) to a methane or acetylene gas discharge plasma in a plasma-enhanced chemical vapor deposition (PECVD) system, the resultant carbon films become super lubricious providing friction coefficients as low as 0.001 or less, an extremely low value [14]. Figure 1 shows the frictional trace of one of these films in dry nitrogen environment. This film was deposited on a sapphire substrate and the counterface ball was also made of a sapphire ball coated with the same DLC film. In moist air, the friction coefficient of the same pair was 20 to 60 times higher. This film was derived from a gas discharge plasma that consisted of 75% hydrogen and 25% methane. The same quality films could be produced from other hydrocarbon gases as well. In the case of acetylene, the gas mixture consisted of 90% hydrogen and 10% acetylene [18].

Besides its exceptional frictional properties, the new carbon film has excellent wear life. In a lifetime test, a 1 micrometer thick film lasted for a sliding distance of over 1300 km or 17.5 million cycles, translating into a wear rate of $5x10^{-11}$ mm^3/N.m [15]. From a tribological standpoint, a combination of extreme wear resistance and superlow friction coefficient is extremely desirable but seldom achieved for most tribological applications. The new carbon film developed in our laboratory combines both of these qualities; thus it is scientifically very interesting. It may also be useful for a wide range of commercial applications. Scientifically, the film provides a rare opportunity to shed some lights into very complex nature of friction and frictional interactions between sliding surfaces. Commercially, if the films of similar qualities are produced and if they can afford superlow friction and wear properties to sliding surfaces in open or moist air, then the range of application possibilities will be enormous and we are working to develop such films in our laboratory.

For the case of superlow friction DLC film produced in our laboratory, we proposed a mechanistic model illustrated in Figure 2. Because of the very unique deposition conditions and source gas composition, we feel that these films are chemically extremely inert and do not interact with sliding counterface surfaces in an adhesive or chemical bonding manner. Specifically, we feel that when such films are grown in a highly hydrogenated hydrocarbon plasmas (such as methane or acetylene), all the sigma or covalent bonds that are free are neutralized and hence there is no such sigma bond interactions between these sliding surfaces. Furthermore, since these films are grown in plasmas containing 10 hydrogen per carbon atom, it is quite possible that some of the surface carbon atoms are di-hydrated or bonded to two hydrogen atoms. Such an over saturation of carbon atoms at or near the sliding surfaces is expected to provide a higher degree of passivation and hence lower friction.

The third important point to remind is that since the DLC films are, in general, dielectric, their sliding surfaces can certainly accumulate static electrical charge during sliding. The main question to answer is whether these charges will cause attraction or repulsion. When the free electrons of hydrogen atoms pair with the sigma bonds of surface carbon atoms, the electrical charge density is permanently shifted to the other side of the nucleus of the hydrogen atom and away from the surface. Such a shift in charge density allows the positively charged hydrogen proton in its nucleus to be closer to the surface than the electron that is used up by the sigma bond of the surface carbon atoms. Therefore, the creation of such a dipole configuration at the sliding interface should give rise to repulsion rather than attraction between the hydrogen-terminated sliding surfaces of the DLC films. The full paper will focus on recent research findings in our laboratory and will emphasis the importance of fundamental research in not only the formulation of these films but also the elucidation of their superlow-friction and wear mechanisms.

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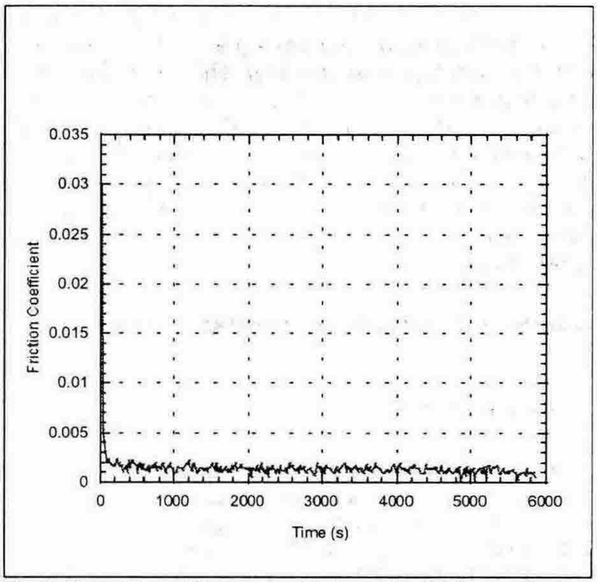

Fig. 1 Variation of friction coefficient of a 6.35 mm diameter sapphire ball during sliding against a sapphire disk in dry nitrogen environment. Both the ball and the disk surfaces were coated with the new DLC film. The film thickness was 1 micrometer and the specific test conditions were: Load, 10 N; Speed, 0.3 m/s, Temperature, 22°C).

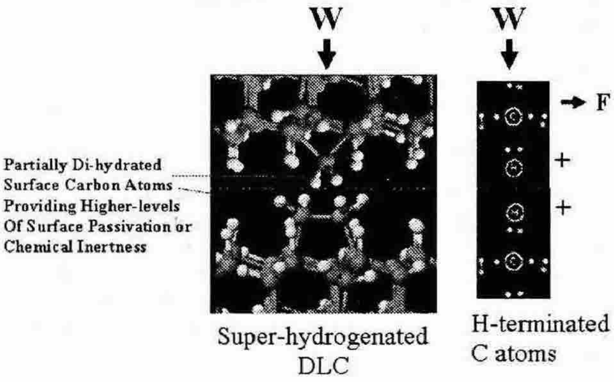

Fig. 2. Illustration of super hydrogenated DLC surfaces sliding against one another.