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SUPERLUBRICITY AND NEAR-WEARLESS SLIDING IN CARBON FILMS

Erdemir, A.

Argonne National Laboratory
Energy Technology Division
Tribology Section
Argonne IL, USA

ABSTRACT

Systematic studies on carbon-based materials and coatings in our laboratory over the past 15 years have led to the discovery of an amorphous carbon film that can provide friction coefficients as low as 0.001 and wear rates of less than 10^{-10} mm^3/N.m when tested in inert or vacuum test environments. This paper provides an overview of the recent progress made in the synthesis and characterization of such films and of the importance of near-surface chemistry and chemical interactions on friction and wear. Based on extensive surface analytical and tribological studies, a mechanistic model is proposed to explain the superlubricity and near-wearless sliding behavior of these carbon films.

Key words: superlubricity, carbon films, lubrication mechanism, wear.

1. INTRODUCTION

Numerous carbon films (diamond, diamondlike carbon (DLC), carbon nitride, etc.) are now available from various sources. While some of them can provide friction coefficients less than 0.01, others can exhibit friction coefficients of 0.7 or higher, especially in inert test environments [1]. Such a large disparity in the frictional behavior of these films is rather intriguing and has often been attributed to the subtle differences in their structure and/or chemistry (intrinsic factors). In particular, the relative amounts of hydrogen and the degree of sp^2 vs. sp^3 hybridization in their structure are often thought to be the main reasons. It is also well-documented that test conditions (extrinsic factors) can strongly affect the friction and wear of these films. Overall, the frictional behavior of most DLC films appears to be a complex interplay between intrinsic and extrinsic factors. Realizing the importance of these factors, we were able to synthesize a DLC film in our laboratory that can consistently give friction coefficients below 0.01 [1]. Accordingly, this paper presents an overview of recent progress in the synthesis and characterization of such films, followed by a discussion of the effect of intrinsic and extrinsic factors on friction and wear. Based on extensive surface analytical and tribological studies, an attempt is also made to elucidate the friction and wear mechanisms of these carbon films.

2. SUPERLUBRICITY IN CARBON FILMS

As mentioned above, extrinsic (environment and test condition specific) and intrinsic (film specific) factors play significant roles in the friction and wear of most carbon films. Surface roughness may also adversely affect friction and needs to be minimized. Extrinsically, the presence or absence of certain chemical species in the surrounding atmosphere is very important. Other extrinsic factors such as temperature, speed, and contact pressure can also play a major role in friction [2]. Intrinsically, the degree of sp^2 vs. sp^3 bonding between neighboring carbon atoms and the amount of hydrogen and/or other elemental species (N, B, F, etc.) within the structure can also influence friction [3,4].

By controlling or eliminating the types of intrinsic and extrinsic sources of friction mentioned above, one should be able to attain superlow friction and wear in carbon films. Most of the intrinsic or film-specific factors can be controlled by effectively controlling the deposition parameters and source gas chemistry during the synthesis of carbon films. Among others, the use of excess hydrogen during film growth was found to be extremely effective in the elimination of dangling σ-bonds that increase interfacial adhesion and hence friction [4]. To produce carbon films with superlow friction, one should also use additional hydrogen (i.e., 50 to 90 vol.%) during film growth.

The results of extensive friction and wear tests on these films in our laboratory indicate a close correlation between the friction and wear coefficients of the DLC films and the hydrogen-to-carbon (i.e., H/C) ratios of the source gas plasmas from which these DLC films were derived [1]. In general, the higher the H/C ratios of the source gases, the lower the friction coefficients of the DLC films. The lowest friction coefficients, i.e., 0.001-0.005, were exhibited by near-frictionless carbon (NFC) films grown in plasmas that contained 75 to 90% hydrogen. Figure 1 shows the typical friction coefficient of a highly optimized NFC film produced on a sapphire substrate. Films grown in hydrogen free or poor plasmas exhibited friction coefficients of more than 0.6, while sapphire on itself had a friction coefficient of 0.9 when tested under the same conditions. The wear rates of such films were in the range of 10^{-11} to 10^{-10} mm^3/N.m.

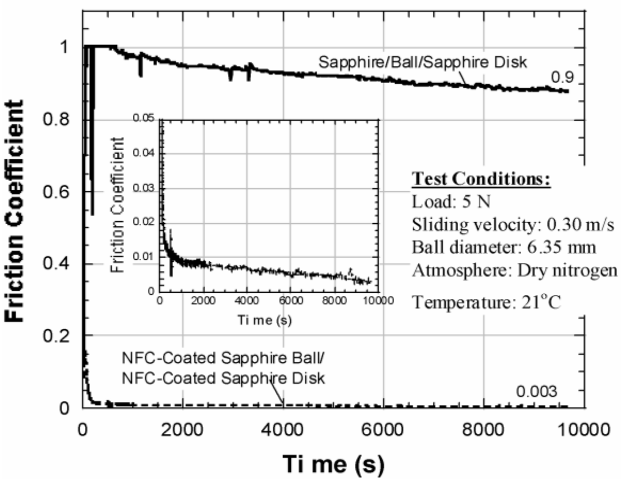

Fig. 1. Typical frictional behavior of a carbon film derived from a highly hydrogenated methane plasma. Inset shows the progression of actual friction trace of carbon film with time. For comparison, the frictional behavior of uncoated sapphire test pair is also provided.

Based on these observations, the following mechanism is proposed to explain the role of hydrogen in the frictional behavior of DLC films. It is well known that hydrogen has a strong chemical affinity toward carbon. Specifically, hydrogen bonds strongly to carbon atoms and thus effectively passivates its un-occupied or free σ-bonds on the surface. Once passivated, such surfaces become chemically inert, causing very little adhesive interactions and hence friction during sliding. Since the deposition of these carbon films is done in a highly hydrogenated methane plasma (i.e., about 10 hydrogen atom to each carbon atom), some of the carbon atoms (at least those on the surface) could be di-hydrogenated, so that two hydrogen atoms would be bonded to a carbon atom on the surface. This condition can occur under the influence of energetic hydrogen ion bombardment during film growth. The existence of di-hydrogenated carbon atoms on the surface will further increase the hydrogen density of these surfaces and thus provide better passivation and hence superlow friction. Such a model is presented in Fig. 2. Recent surface analytical studies have confirmed that these films are indeed highly hydrogenated (containing up to 40 at.% hydrogen) and thus intrinsically very favorable to lower friction. Overall, fundamental tribological and surface analytical studies have revealed that hydrogen (within the bulk or on the sliding surfaces) is extremely important for the superlubricity and near-wearless sliding behavior of DLC films.

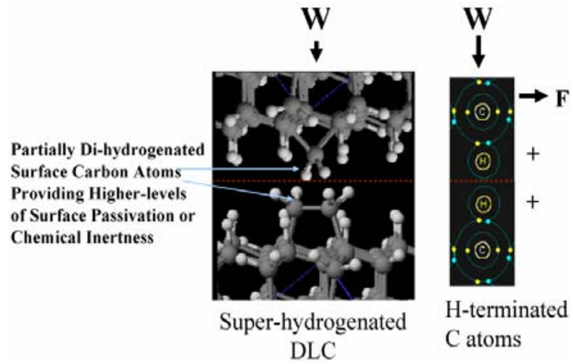

Fig. 2. Schematic representation of highly hydrogenated DLC surfaces leading to superlubricity.

3. SUMMARY

There is no doubt that hydrogen plays a critical role in the frictional behavior of most carbon films in general and DLC films in particular. By controlling intrinsic (film specific) and extrinsic (test condition specific) factors, superlow friction and wear should be possible in these films.

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