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SOLID LUBRICATION BY MULTIWALLED CARBON NANOTUBES IN AIR AND IN VACUUM FOR SPACE AND AERONAUTICS APPLICATIONS

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ABSTRACT

To evaluate recently developed aligned multiwalled carbon nanotubes (MWNTs) and dispersed MWNTs for solid lubrication applications, unidirectional sliding friction experiments were conducted with 440C stainless steel balls and hemispherical alumina-yttria stabilized zirconia pins in sliding contact with the MWNTs deposited on quartz disks in air and in vacuum. The results indicate that MWNTs have superior solid lubrication friction properties and endurance lives in air and vacuum under dry conditions. The coefficient of friction of the dispersed MWNTs is close to 0.05 and 0.009 in air and in vacuum, respectively, showing good dry lubricating ability. The wear life of MWNTs exceeds 1 million passes in both air and vacuum showing good durability. In general, the low coefficient of friction can be attributed to the combination of the transferred, agglomerated patches of MWNTs on the counterpart ball or pin surfaces and the presence of tubular MWNTs at interfaces.

Keywords: Carbon Nanotube, Solid Lubricant, Friction, Wear Life, Vacuum

INTRODUCTION

Carbon nanotubes (CNTs) may be either single- or multiwalled. Both types possess remarkable physical, electronic, and thermal properties. For example, the Young's modulus of single-walled CNTs lies close to 1 TPa, and the maximum tensile strength is close to 30 GPa [1], with values for multiwalled CNTs being somewhat less. The precise values depend upon the CNT diameter, length, chirality, and number of walls and defects. Their intriguing structures have sparked much excitement in recent years, and a large amount of research has been dedicated to understanding them. Although the CNTs are still in the early stages of development in the field of tribology, tribological applications may emerge from such areas as solid lubricant films, additives for liquid lubricants and greases, and composites for wear parts [2]. The primary objective of this report is to investigate the steady-state coefficient of friction and endurance (lifetime) of multiwalled carbon nanotubes (MWNTs), such as aligned MWNTs, dispersed nongraphitized MWNTs, and dispersed graphitized MWNTs, deposited on quartz disk substrates.

MATERIALS

The aligned MWNTs were synthesized within a high-temperature tube furnace around 1073 K on iron-coated quartz substrates. The dispersed, nongraphitized MWNT and dispersed, graphitized MWNT coating films were prepared by deposition on quartz disks with the dilute MWNT suspension followed by evaporation of solvent under dry nitrogen flow. Coating films with four different relative thicknesses (0.63, 1.26, 1.89, and 2.52 $\mu g \cdot mm^{-2}$) were fabricated. Unless otherwise specified, MWNT coating films with the standard thickness of 2.52 $\mu g \cdot mm^{-2}$ were used in most experiments.

EXPERIMENT

The ball-on-disk and pin-on-disk tribometer used in the investigation was mounted in a vacuum chamber. Unidirectional sliding friction experiments were conducted with the aligned MWNT coatings and the dispersed MWNT (nongraphitized and graphitized) coatings at room temperature in air (~50 percent relative humidity) and in vacuum ($\sim 7 \times 10^{-6}$ Pa). All experiments were conducted with 6-mm-diameter 440C stainless steel balls and 6-mm-diameter rounded surface at apex of alumina-yttria stabilized zirconia pins in sliding contact with the MWNT films deposited on quartz disk substrates. All experiments were conducted with a load of 1.4 N, at a track diameter of 6 mm, and at a sliding velocity of 38 $mm \cdot s^{-1}$. The sliding wear life (endurance life) for the MWNT coatings was determined to be the number of passes at which the coefficient of friction rose to 0.15 in a given environment.

Postwear analyses of wear surfaces, transfer films, wear debris, and microstructures were conducted using high-resolution transmission electron microscopy (HRTEM), electron energy loss spectroscopy (EELS), scanning electron microscopy (SEM), energy-dispersive x-ray spectroscopy (EDS), and vertical scanning interferometry (VSI).

RESULTS AND DISCUSSION

Aligned MWNTs — In air, the steady-state coefficient of friction for the aligned MWNT coating in contact with 440C stainless steel was between 0.025 and 0.060. The average coefficient of friction was 0.04, which is one-fourth to one-fifth of the average coefficient of friction for bare quartz or iron-coated quartz. The wear life of the typical MWNT coating was 172,500 passes. Although the wear scar contained transferred MWNTs, SEM observations revealed almost no wear of 440C stainless steel and quartz disks themselves even after 100,000 passes.

In vacuum, the steady-state coefficient of friction for the aligned MWNT coating in contact with alumina-yttria stabilized zirconia was between 0.073 and 0.11, while that for bare quartz fluctuated between 0.17 and 0.46 and that for iron-coated quartz fluctuated between 0.18 and 0.53. The average coefficient of friction for the aligned MWNT coating in contact with alumina-yttria stabilized zirconia was 0.09, nearly one-third to one-fourth of those for bare quartz and iron-coated quartz disks. The wear life of the typical aligned MWNT coating in contact with alumina-yttria stabilized zirconia was about 5700 passes.

Dispersed MWNTs — In air, the average coefficient of friction for the dispersed, nongraphitized MWNT coating in contact with alumina-yttria stabilized zirconia was 0.06. The wear life of this particular nongraphitized MWNT coating was greater than 3.5 million passes. Although most fine MWNT cylinders were plowed out and piled at both sides of the wear track, a small amount of MWNTs were cut or broken by sliding action and remained in the wear track. The smeared, agglomerated MWNT layers seen in the wear track of the aligned MWNT coating are absent from the dispersed, nongraphitized MWNTs. The transferred plate-like, smeared, agglomerated patches of MWNTs were found in the wear scar and at the edges of the wear scar. Although the wear scar contained such transferred MWNT patches, it revealed almost no wear of the alumina-yttria stabilized zirconia itself.

In vacuum, the steady-state coefficient of friction for the dispersed, graphitized MWNT coating in contact with alumina-yttria stabilized zirconia showed several phases of frictional evolution; the average coefficient of friction was 0.009 in the first phase, 0.027 in the second phase, 0.044 in the third phase, and 0.027 in the fourth phase over 1 million passes. The wear life of this particular graphitized MWNT coating was greater than 1 million passes. SEM observations revealed that both the surfaces of the quartz disk and alumina-yttria stabilized zirconia pin were covered with agglomerated patches of MWNTs and were protected from wear because of no direct contact between these surfaces.

HRTEM images for a set of wear-debris samples collected from the wear track of an aligned MWNT coating batch are consistent with an increased duration of experimental sliding time in that they show an increasing amount of amorphous carbon, cut MWNTs, and MWNTs with fractured walls generated by increased sliding friction duration. The plastic deformation and cracks subdivide and fragment the multiwalled structure of MWNTs. It is also possible that the fragmented nanotube walls behave similar to the low energy surfaces produced when graphite is used as a solid lubricant. The nature of the strain or structural surface damage of MWNTs varies with depth from the surface. The thickness of the deformed layer and degree of deformation in the multiwalls are functions of the sliding friction duration.

SOLID LUBRICATION MECHANISMS

The presence of a thin transfer film provided a low coefficient of friction. The presence of the MWNT cylinders in the wear track, in which amorphous carbon layers were formed upon the exterior of the MWNTs during sliding, also contributed to the coefficient of friction. In general, the low coefficient of friction can be attributed to the combination of the transfer film and/or tubular MWNTs.

Three factors contribute toward reducing the coefficient of friction and providing good, durable performance: (1) Friction resistance may be minimized by the partial rolling motion of the MWNTs or broken MWNTs in the wear track; (2) The real area of contact is minimized by the high elastic modulus of the MWNTs, alumina-yttria stabilized zirconia, and quartz; and (3) The surface energy at the interface is minimized by the residual MWNTs.

CONCLUSIONS

MWNTs had good friction properties and endurance lives in air and in vacuum under dry conditions. The coefficient of friction of dispersed, nongraphitized MWNTs in air and dispersed, graphitized MWNTs in vacuum is close to 0.06 and 0.009, respectively. The wear life of both MWNTs exceeds 1 million passes in air and in vacuum showing good durability.

The dispersed, graphitized MWNT coating exhibited better friction and wear life performance than those of the aligned MWNTs in vacuum. The results indicate that prearranged or prepatterned nanostructure, such as that of the aligned MWNT coating, is not necessary for MWNTs to provide a low coefficient of friction, that is, solid-film lubrication.

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