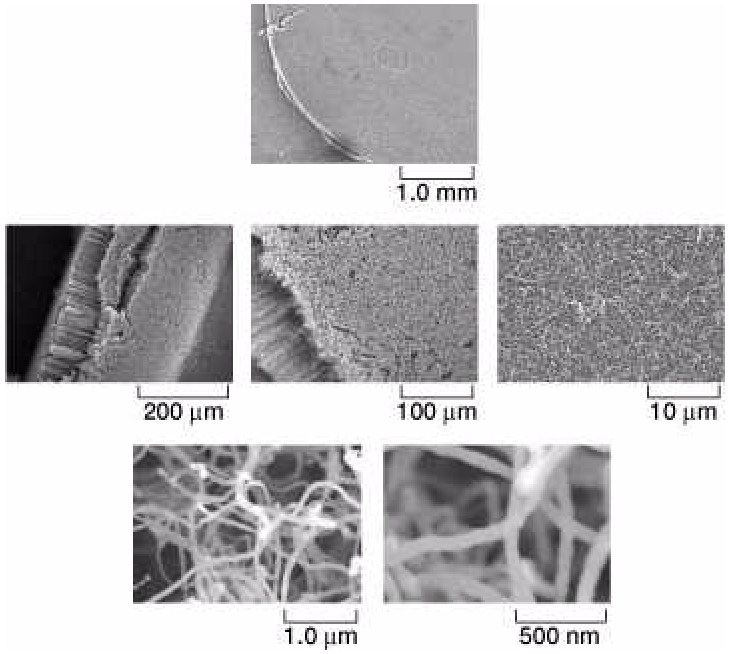
New Effective Material Couple--Oxide Ceramic and Carbon Nanotube--Developed for Aerospace Microsystem and Micromachine Technologies

The prime driving force for using microsystem and micromachine technologies in transport vehicles, such as spacecraft, aircraft, and automobiles, is to reduce the weight, power consumption, and volume of components and systems to lower costs and increase affordability and reliability (refs. 1 and 2). However, a number of specific issues need to be addressed with respect to using microsystems and micromachines in aerospace applications--such as the lack of understanding of material characteristics; methods for producing and testing the materials in small batches; the limited proven durability and lifetime of current microcomponents, packaging, and interconnections; a cultural change with respect to system designs; and the use of embedded software, which will require new product assurance guidelines.

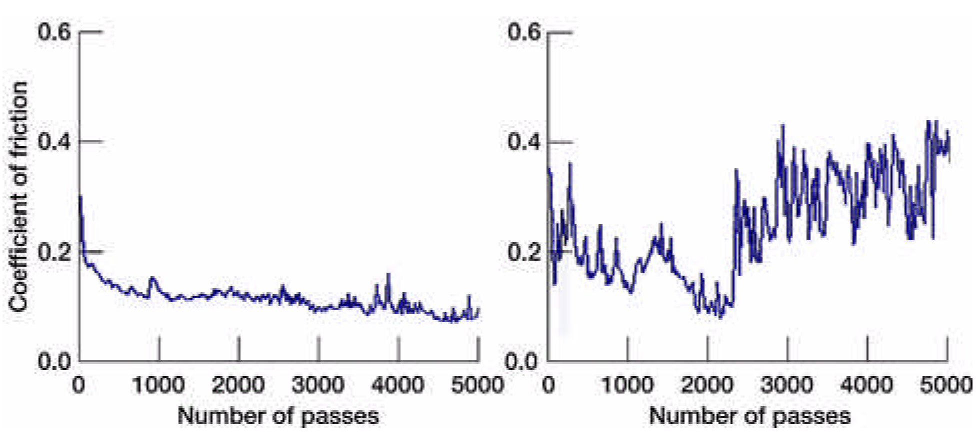
In regards to material characteristics, there are significant adhesion, friction, and wear issues in using microdevices. Because these issues are directly related to surface phenomena, they cannot be scaled down linearly and they become increasingly important as the devices become smaller (ref. 2). When microsystems have contacting surfaces in relative motion, the adhesion and friction affect performance, energy consumption, wear damage, maintenance, lifetime and catastrophic failure, and reliability. Ceramics, for the most part, do not have inherently good friction and wear properties. For example, coefficients of friction in excess of 0.7 have been reported for ceramics and ceramic composite materials (e.g., ref. 3).

Under Alternate Fuels Foundation Technologies funding, two-phase oxide ceramics (ref. 4) developed for superior high-temperature wear resistance in NASA's High Operating Temperature Propulsion Components (HOTPC) project and new two-layered carbon nanotube (CNT) coatings (CNT topcoat/iron bondcoat/quartz substrate) developed in NASA's Revolutionary Aeropropulsion Concepts (RAC) project have been chosen as a materials couple for aerospace applications, including micromachines, in the nanotechnology lubrication task because of their potential for superior friction and wear properties in air and in an ultrahigh vacuum, spacelike environment. At the NASA Glenn Research Center, two-phase oxide ceramic eutectics, Al_2O_3/ZrO_2 (Y_2O_3), were directionally solidified using the laser-float-zone process (ref. 5), and carbon nanotubes were synthesized within a high-temperature tube furnace at 800 °C (ref. 6). Physical vapor deposition was used to coat all quartz substrates with 5-nm-thick iron as catalyst and bondcoat, which formed iron islands resembling droplets and serving as catalyst particles on the quartz.



Carbon nanotube materials showing oriented growth.
Six scanning electron micrographs showing oriented growth-single strands to twisted fibers to dense, pilelike mats.

The preceding figure presents a series of scanning electron micrographs showing multiwalled carbon nanotubes directionally grown as aligned "nanograss" on quartz. Unidirectional, sliding friction experiments were conducted at Glenn with the two-layered CNT coatings in contact with the two-phase Al_2O_3/ZrO_2 (Y_2O_3) eutectics in air and in ultrahigh vacuum (see the following graphs). The main criteria for judging the performance of the materials couple for solid lubrication and antistick applications in a space environment were the coefficient of friction and the wear resistance (reciprocal of wear rate), which had to be less than 0.2 and greater than 10^5 N·m/mm^3, respectively, in ultrahigh vacuum.



Coefficient of friction for carbon nanotube coating and quartz substrate in sliding contact with an Al_2O_3/ZrO_2 (Y_2O_3) eutectic (two-phase oxide ceramic) hemispherical pin in ultrahigh vacuum. Left: Carbon nanotube coating on quartz (CNT/iron/quartz). Right:

Uncoated quartz.
Two graphs of coefficient of friction (from about 0.1 to 0.4) versus number of passes (from 0 to 5000).

In air, the coefficient of friction for the CNT coatings in contact with Al_2O_3/ZrO_2 (Y_2O_3) eutectics was 0.04, one-fourth of that for quartz. In an ultrahigh vacuum, the coefficient of friction for CNT coatings in contact with Al_2O_3/ZrO_2 (Y_2O_3) was one-third of that for quartz. The two-phase Al_2O_3/ZrO_2 (Y_2O_3) eutectic coupled with the two-layered CNT coating met the coefficient of friction and wear resistance criteria both in air and in an ultrahigh vacuum, spacelike environment. This material's couple can dramatically improve the stiction (or adhesion), friction, and wear resistance of the contacting surfaces, which are major issues for microdevices and micromachines.

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