Nanotribology and MEMS

The tribological phenomena of adhesion, friction, and wear arise when solid objects make contact. As the size of devices shrinks to micro- and nanoscales, the surface-to-volume ratio increases and the effects of body forces (gravity and inertia) become insignificant compared with those of surface forces (van der Waals, capillary, electrostatic, and chemical bonding). In microelectromechanical systems (MEMS), tribological and static interfacial forces are comparable with forces driving device motion. In this situation, macroscale lubrication and wear mitigation methods, such as the use of bulk fluids and micrometer thick coatings, are ineffective; new nano-engineering approaches must be employed for MEMS devices with moving structures. We review fundamental tribological problems related to micro- and nanoscale mechanical contacts and developments in MEMS lubrications.

Seong H. Kim[1]*, David B. Asay[1], and Michael T. Dugger[2]

[1]Department of Chemical Engineering, The Pennsylvania State University, University Park, PA 16802, USA

[2]Sandia National Laboratories, Albuquerque, NM 87185, USA

**E-mail: shkim@engr.psu.edu*

MEMS with movable structures were first demonstrated in the late 1980s when researchers at the University of California, Berkeley illustrated the use of standard integrated circuit fabrication technologies to produce pin joints, gears, and sliders[1]. These structural elements were subsequently used to produce an electrostatic micromotor based on previous design considerations from researchers at AT&T Bell Laboratories[2,3]. This first device consisted of a rotor 60 μm in diameter and 1 μm thick, surrounded by stator elements separated from the rotor by 2 μm gaps. Application of voltage pulses to the stator elements in the proper sequence allowed the rotor to spin. Although these devices were built with low friction design and materials, motion of these small devices was possible only with high drive voltages. Thus the development of the first mechanically complex micromachine was accompanied by the first manifestation of friction-related problems in micromachines.

The first efforts in MEMS fabrication were followed by a burgeoning of research activities in design, fabrication, control, and operation of micromachines in the early 1990s. In fact, there are some notable commercial successes in MEMS that impact the lives of millions of

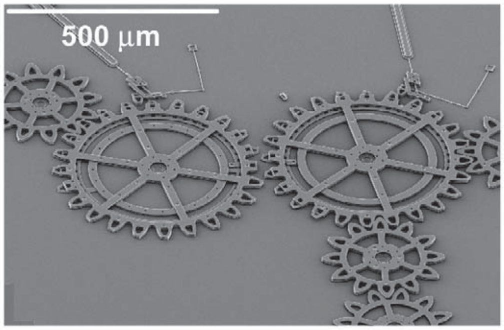
 ISSN:1748 0132

people every day. For example, every new automobile sold since the late 1990s uses one or more micromachined accelerometers to deploy airbags in the event of a crash. The accelerometer works by measuring the voltage required to keep a suspended mass at its rest position. In this device, there are no deliberately contacting surfaces once in service[4]. The low-cost color printer market has been dominated by MEMS since the late 1990s. Microfabricated channels deliver liquid ink near an exit aperture, where an electrical pulse on a heater near the exit rapidly forms a bubble and ejects a droplet of ink of well-controlled size out of the exit aperture[5]. This device does not employ contacting surfaces, but fluid erosion caused by the flow of ink containing pigment particles is an issue. In the late 1990s, high-definition projectors and televisions came to market employing a light-modulating MEMS device[6]. This device consists of hundreds of thousands to millions of individual Al mirrors mounted on torsional hinges that can be tilted to reflect light towards a screen, or away from the screen for a dark pixel. Unlike the applications described above, this device does rely on contact between surfaces during normal operation. Each time a mirror changes its tilt angle, the mirror touches a landing tip to hold the mirror at a known stop position. The flexural motion of the support structure inevitably causes some minor rubbing action a few tens of nanometers wide. Even at this small rubbing amplitude, wear and excessive adhesion are observed unless careful surface treatments are employed. In this case, the mirrors are sealed inside a package with perfluorodecanoic acid[6]. A solid at room temperature, this material vaporizes at operating temperature because of the high intensity lamp shining on the mirrors, and is thereby able to redistribute within the package and passivate any Al surfaces that become exposed during operation.

Commercially successful MEMS devices, to date, have either nonmoving parts or contacts whose lateral motion is very restricted. Many more exciting applications can be attained with MEMS devices consisting of moving, touching, and rubbing structures. These include gears and motors that can enable much more complicated mechanical functions at the micro- and nanoscale. Examples shown in Fig. 1 are parts of an electromechanical lock and a light-steering mirror. However, the effects of adhesion, friction, and wear of MEMS devices are challenging the development and commercialization of more sophisticated micromachines. Tribological problems associated with micromachines cannot be resolved by applying conventional lubrication methods used in the macroscale, such as liquid lubricants. In micromachines, the viscosity of liquid lubricants causes severe power dissipation problems and makes devices move slowly, negating one of the principal advantages of micromachines, i.e. low inertia that enables rapid mechanical switching.

The tribological behavior of contacts in MEMS technologies differs from those in macroscopic engineering structures. At the macroscopic scale, millions of asperities give rise to the parametric relationships that we are familiar with, such as Amonton's law, which states that the friction coefficient is independent of contact area and applied load. In MEMS, real mechanical contacts typically consist of a few nanometer-scale asperities that touch. At these small scales, Amonton's law breaks down and individual asperity contact behavior must be considered. Additionally, forces that are negligible at the macroscale become significant at the microscopic scale and smaller. These include electrostatic or van der Waals forces between contacting and noncontacting surfaces, and capillary forces because of liquid menisci[7]. As an example, Fig. 2 compares the magnitude of gravitation and adhesion forces as a function of size[8]. At the macroscopic

(a)



(b)

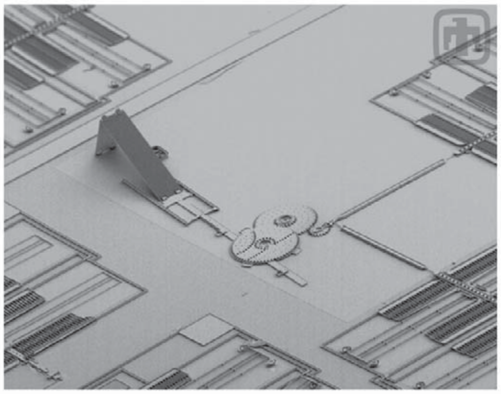


Fig. 1 (a) Intermeshing gears and (b) mirror and drive systems produced by Si surface micromachining in Sandia National Laboratories' SUMMiT™ process.

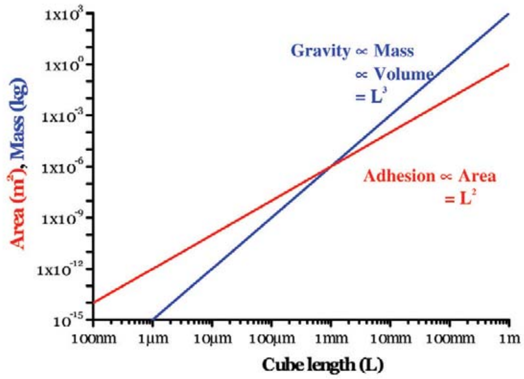


Fig. 2 Variation of gravity and adhesion for a cube with a smooth surface as a function of size (L). Adhesion force falls linearly with surface or contact area while gravitational force falls with volume[8].