<u>NANOTRIBOLOGY</u> - The road to no WEAR!

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Feynman once said "**there is plenty of room at the bottom**". Today we experience the relevance of this statement with the improvement in properties with decreasing size observed in the field of Nanotechnology. Nanotechnology literally means any technology performed at the nanoscale that has applications to the real world. Going from macro to micro scale, the surface area to volume ratio increases considerably and the surface forces such as fiction, adhesion, meniscus forces, viscous drag, and surface area significantly increase.
With advances in technology the size of mechanical, electrical and optical components is reducing at a very fast pace. Incorporation of sensing and computing to actuation is currently in it's early stages. Rapid actuation requires fast moving interacting surfaces. Current advances in magnetic storage devices, MEMS, nanotechnology, micro-engines, all involve basic issues of friction, wear, adhesion and lubrication. The need to miniaturize the components has presented challenges and the importance of tribology at a proportionate scale is being felt. This advent of micro/nanostructures and the subsequent miniaturization of moving components for various nanotechnology applications have ascribed paramount importance to the tribology and mechanics on the nanoscale. Materials with low friction and adhesion are desirable. And hence "Nanotribology" is today one of the most important mechanical technology. So to understand nanotribology it is important to first define tribology.
"Tribology" is a combination of two Greek words - "tribo" and "logy". "Tribo" means rubbing and "logy" means knowledge. The Greeks originally applied it to understand the motion of large stones across the earth's surface. Today tribology plays a critical role in diverse technological areas - in the advanced technological industries of semiconductors and data storage, tribological studies help to optimize polishing processes and lubrication of the data storage substrates. Tribology helps to increase the lifespan of mechanical components. However many industrial processes require a detailed understanding of tribology at the nanometer scale. The development of lubricants in the automobile industry depends on adhesion of nanometer layers or monolayers to the material surface. Assembly of components can depend critically on the adhesion of materials at the nanometer length scale. Hence nanotribology stands out as a strong branch of nanotechnology and has become strongly essential to study today.

Technical definition of Nanotribology: Nanotribology can be defined as the investigations of interfacial processes, on scales ranging in the molecular and atomic scale, occurring during adhesion, friction, scratching, wear, nanoindentation, and thin-film lubrication at sliding surfaces.

What is the need for nanotribology?

Tribology is one of the oldest sciences and is still not very well understood. Nanotribological studies reveal behavior that can be quite different from those observed at macroscopic levels. Study of tribological behavior can help us control and manipulate matters at nanoscale. We can take advantage of the new electronic and atomic interactions as well as new properties like magnetic and mechanical properties observed at nano-levels for synthesis, assembling and processing of nanoscale building blocks, composites, coatings, porous materials, smart materials with in built condition based maintenance and self-repair, self cleaning surfaces with reduced and controlled friction, wear and corrosion.
<u>For advanced health care:</u> to modify surfaces in order to create structures that control interaction between materials and biological systems
<u>For energy conversion and storage:</u> nanoscale carbide coatings, self-assembled layers for friction control, materials performances at nano- and MEMS scale as a function of aging. For in-situ lubrication study and control. For advancements in ultra low flying head disk interfaces
<u>Microcraft space exploration and industrialization:</u> to make self repairing materials and self-replicating, biomemmetic materials and nanoscale devices which can sustain any need for movement of sliding surfaces for long periods under severe conditions. Also ultra light weight and ultra strong materials with unique properties for required for demanding projects.

How to study nanotribology?

Traditionally, to characterize friction, lubrication and wear, a tribometer having several configurations such as pin on disc, ball on flat, or flat on flat was used. However, generating motion at the nanometer scale is extremely challenging. Therefore the need for new characterization techniques was felt.

Nanotribology today, widely uses many new instruments designed over the last 50 years, such as the SFA, STM, AFM, and the FFM.

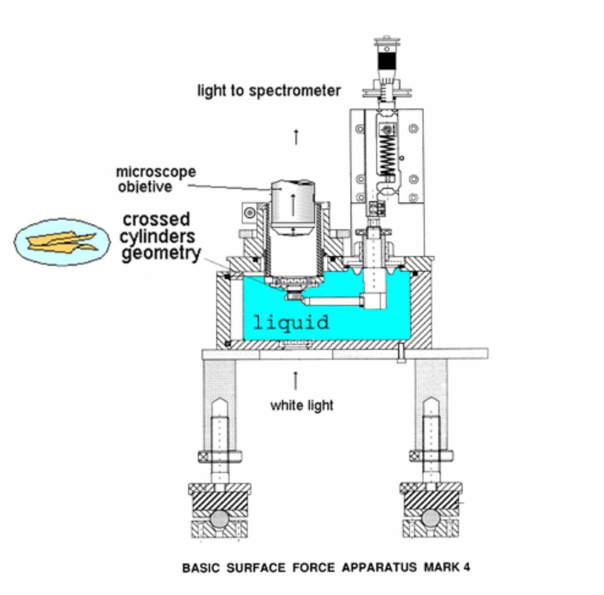
SFA or the surface force apparatus was developed in the 1960's and has been commonly used to study the static and dynamic properties of molecularly thin films sandwiched between two molecularly smooth surfaces.
The scanning tunneling microscope or the STM was developed in 1981 and has since then been used to image clean conducting surfaces and lubrication molecules. The STM has a resolution in the atomic level.
AFM: The atomic force microscope was invented in the year of 1985 and its common uses include

-measuring ultra-small forces between probe tip and the surface.

-topographical measurements on the nanoscale
-adhesion force measurements
-electrostatic force measurements
-investigating scratching, wear and indentation
-detection of transfer of material
-boundary lubrication (for scan areas greater than 10 micrometer square, one can use ellipsometry for thickness measurements)
-fabrication and machining

The friction force microscope or the FFM is a modified form of the AFM and gives the atomic and micro scale studies of friction and lubrication. The FFM is also known as the LFM (lateral force microscope). It uses a sharp diamond tip mounted on a stiff cantilever beam.

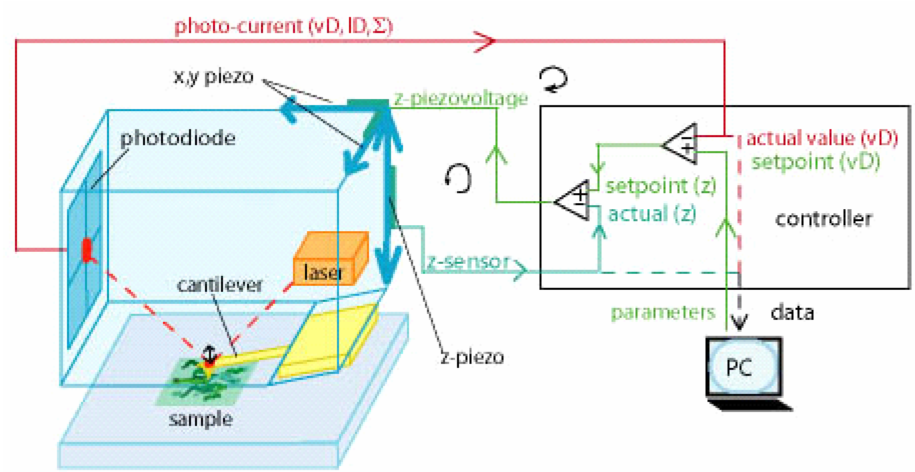
However, AFM is the most commonly used technique to study tribology on the nanoscale, the reason for which will be understood soon.



An introduction to the surface force apparatus (SFA)

The SFA consists of a pair of automatically smooth surfaces, usually mica sheets, which are mounted on crossed cylinders that can be pressed together to form a circular contact under pressure. The mica surfaces can be treated to attach molecules of interest, and the surfaces may be immersed completely wtihin a liquid, or maintained in a controlled environment. Actuators attached to either or both of the surface's supports are used to apply a load or shear force and used to control the distance of separation between them. Sensors are attached to measure the load and friction forces. The contact area and relative separation of the surfaces can be measured with optical or capacitive measurements. The separation distance can be measured and controlled to the angstrom level. The lateral resolution is limited to the range of several micrometers. The instrument is thus a model contact where the contacting geometry is known, the material between the surfaces can be varied, and the interaction forces can be controlled and measured. The drawbacks of the instrument are that the lateral resolution is limited and molecular smoothness is required to obtain meaningful results and so usually the substrate is restricted to mica.

An introduction to the Atomic Force Microscope (AFM) and FFM



The atomic force microscope was developed by Gerd Binnig et al. in 1985. It is capable of investigating surfaces of scientific and engineering interest, on an atomic scale. The AFM relies on a scanning technique to produce very high resolution, three-dimensional images of sample surfaces. AFM measures ultra small forces (less than 1 nN) present between the AFM tip surface mounted on a flexible cantilever beam, and a sample surface. These small forces are measured by measuring the motion of a very flexible nanosized cantilever beam having an ultra small mass, by a variety of measurement techniques including optical deflection, optical interference, capacitance, and tunneling current. The deflection can be measured to within 0.02 nm, so for a typical cantilever force constant of 10 N/m, a force as low as 0.2 nN can be detected. In the operation of high-resolution AFM, the sample is generally scanned rather than the tip because any cantilever movement would add vibrations. AFMs are now available for measurement of large samples, where the tip is scanned and the sample is stationary. To obtain atomic resolution with AFM, the spring constant of the cantilever should be weaker than the equivalent spring between atoms. A cantilever beam with a spring constant of about 1 N/m or lower is desirable. Tips

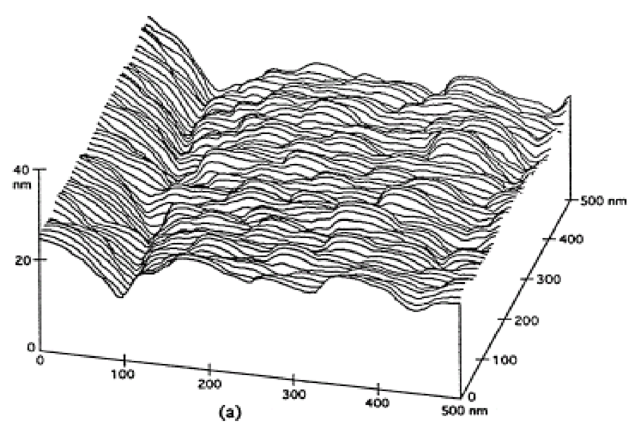
have to be as sharp as possible. Tips with a radius ranging from 10 to 100 nm are commonly available.
Subsequent modifications to AFM led to the development of the friction force microscope or the lateral force microscope (LFM), designed for atomic-scale and microscale studies of friction and lubrication. This instrument measures lateral or friction forces (in the plane of sample surface and in the direction of sliding). By using a standard or a sharp diamond tip mounted on a stiff cantilever beam, AFM is also used in investigations of scratching and wear, indentation, and fabrication/machining. Surface roughness, including atomic-scale imaging, is routinely measured using the AFM. Adhesion, friction, wear and boundary lubrication at the interface between two solids with and without liquid films have been studied using AFM and FFM. Nanomechanical properties are also measured using an AFM. At most solid-solid interfaces of technological relevance, contact occurs at numerous asperities. An AFM/FFM tip sliding on a surface simulates just one such contact.

The AFM is the only of the above introduced techniques capable of investigating almost all aspects of nanotribology and hence it is important to have an understanding of how it does it.

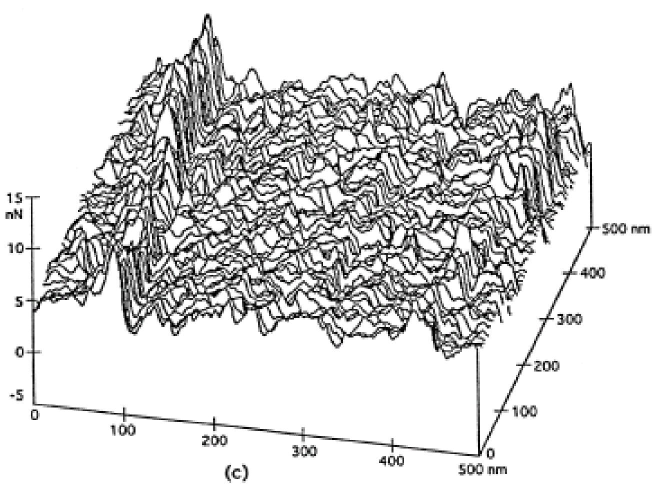
THE USE OF AFM TO STUDY NANOTRIBOLOGY

Surface roughness and friction force measurements

Simultaneous measurements of surface roughness and friction force can be made with the AFM. For such measurements, the sample is mounted on a PZT tube scanner which consists of separate electrodes to scan precisely the sample in the *X*-*Y* plane in a raster pattern and to move the sample in the vertical (*Z*) direction. A sharp tip at the end of a flexible cantilever is brought in contact with the sample. Normal and frictional forces being applied at the tip-sample interface are measured using a laser beam deflection technique. A laser beam from a



AFM - topographic scan of a rough surface diode laser is directed by a prism onto the back of a cantilever near its free end, tilted downward at about 10 degrees with respect to the horizontal plane. The reflected beam from the vertex of the cantilever is directed through a mirror onto a quad photo detector (split photo detector with four quadrants). The differential signal from the top and bottom photodiodes provides the AFM signal which is a sensitive measure of the cantilever vertical deflection. Topographic features of the sample cause the tip to deflect in the vertical direction as the sample is scanned under the tip. This tip deflection will change the direction of the reflected laser beam, changing the intensity difference between the top and bottom photo detector (AFM signal). In the AFM operating mode called the height mode, for topographic imaging or for any other operation in which the applied normal force is to be kept a constant, a feedback circuit is used to modulate the voltage applied to the PZT scanner to adjust the height of the PZT, so that the cantilever vertical deflection (given by the intensity difference between the top and bottom detector) will remain constant during scanning. The PZT height variation is thus a direct measure of the surface roughness of the sample. Many multimode AFMs can be used for topography measurements in the so-called tapping mode, also referred to as dynamic force microscopy. In the tapping mode, during scanning over the surface, the cantilever is vibrated by a piezo mounted above it, and the oscillating tip slightly taps the surface at the resonant frequency of the cantilever (70-400 Hz) with a 20-100 nm oscillating amplitude introduced in the vertical direction with a feedback loop keeping the average normal force constant. The oscillating amplitude is kept large enough so that the tip does not get stuck to the sample because of adhesive attractions. The tapping mode is used in topography measurements to minimize effects of friction and other lateral forces and to measure topography of soft surfaces. For measurement of friction force being applied at the tip surface during sliding, the other two (left and right) quadrants of the photo detector (arranged horizontally) are used. In the so-called friction mode, the sample is scanned back and forth in a direction orthogonal to the long axis of the cantilever beam. A friction force between the sample and the tip will produce

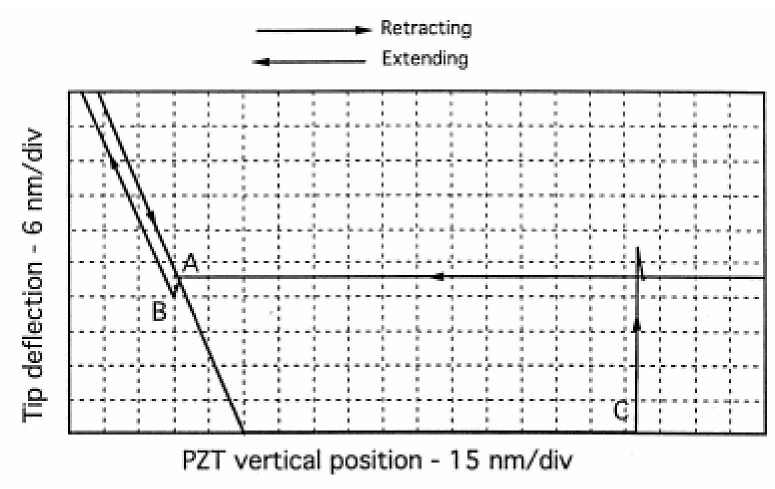


FRICTION FORCE MAP OF THE SAME SURFACE

a twisting of the cantilever. As a result, the laser beam will be reflected out of the plane defined by the incident beam and the beam reflected vertically from an untwisted cantilever. This produces an intensity difference of the laser beam received in the left and right quadrants of the photo detector. The intensity difference between the left and right detectors (FFM signal) is directly related to the degree of twisting and hence to the magnitude of the friction force. One problem associated with this method is that any misalignment between the laser beam and the photo detector axis would introduce error in the measurement. However, by following the procedures in which the average FFM signal for the sample scanned in two opposite directions is subtracted from the friction profiles of each of the two scans, the misalignment effect is eliminated. This method provides 3-D maps of friction force. By following the friction force calibration procedures developed before, voltages corresponding to friction forces can be converted to force units. Coefficient of friction is obtained from the slope of friction force data measured as a function of normal loads typically ranging from 10 to 150 nN. This approach eliminates any contributions due to the adhesive forces. Topographic measurements in the contact mode are typically made using a sharp, microfabricated square pyramidal Si3N4 tip on a cantilever beam with normal stiffness of about 0.5 N/m at a normal load of about 10 nN and friction measurements are carried out in the load range of 10-150 nN. Topography measurements in the tapping mode utilize a stiff cantilever with high resonant frequency; typically a square-pyramidal etched single crystal silicon tip, with a tip radius ranging from 10 to 50 nm, mounted on a stiff rectangular silicon cantilever beam with a normal stiffness of about 50 N/m, is used. To study the effect of radius of a single asperity (tip) on adhesion and friction, micro spheres of silica with radii ranging from about 4 to 15 micrometers are attached with epoxy at the ends of tips of Si3N4 cantilever beams. Scanning speeds in the fast and slow scan directions depends on the scan area and scan frequency. Scan sizes ranging from less than 1 nmX1 nm to 125 micromX125 microm and scan rates from less than 0.5 to 122 Hz typically can be used. Higher scan rates are used for smaller scan lengths. For example, scan rates in the fast and slow scan directions for an area of 10 mmX10 mm scanned at 0.5 Hz are 10 mm/s and 20 nm/s, respectively.

Adhesion measurements

Adhesive force measurements are performed in the so-called force calibration mode. In this mode, force distance curves are obtained. The horizontal axis gives the distance the piezo (and hence the sample) travels and the vertical axis gives

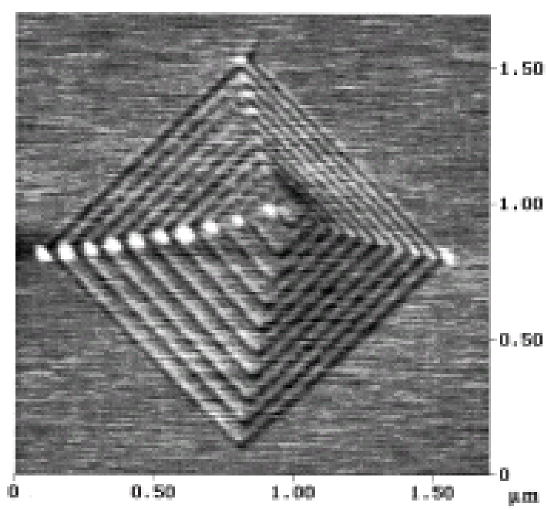


the tip deflection. As the piezo extends, it approaches the tip, which is at this point in free air and hence shows no deflection. This is indicated by the flat portion of the curve. As the tip approaches the sample within a few nanometers (point A), an attractive force exists between the atoms of the tip surface and the atoms of the sample surface. The tip is pulled towards the sample and contact occurs at point B on the graph. From this point on, the tip is in contact with the surface and as the piezo further extends, the tip gets further deflected. This is represented by the sloped portion of the curve. As the piezo retracts, the tip goes beyond the zero deflection (flat) line because of attractive forces (van der Waals forces and long range meniscus forces), into the adhesive regime. At point C in the graph, the tip snaps free of the adhesive forces, and is again in free air. The horizontal distance between points B and C along the retrace line gives the distance moved by the tip in the adhesive regime. This distance multiplied by the stiffness of the cantilever gives the adhesive force. Incidentally, the horizontal shift between the loading and unloading curves results from the hysteresis in the PZT tube.

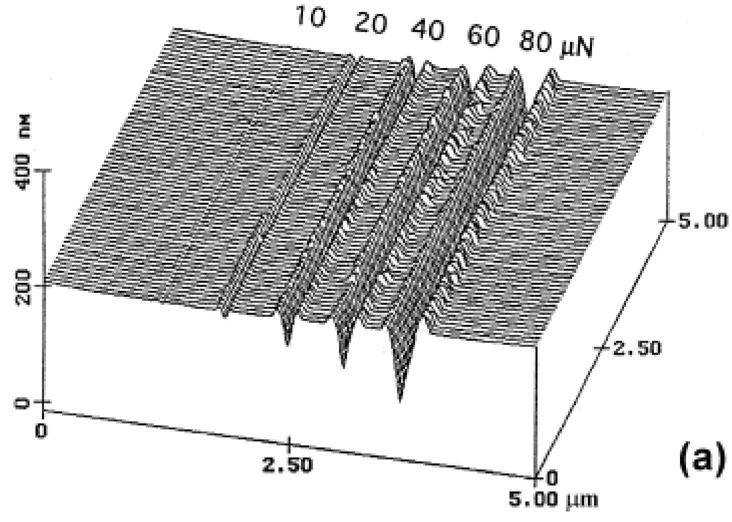
Scratching, wear and fabrication / machining

For microscale scratching, microscale wear, nanofabrication/nanomachining and nanoindentation hardness measurements, an extremely hard tip is required. A

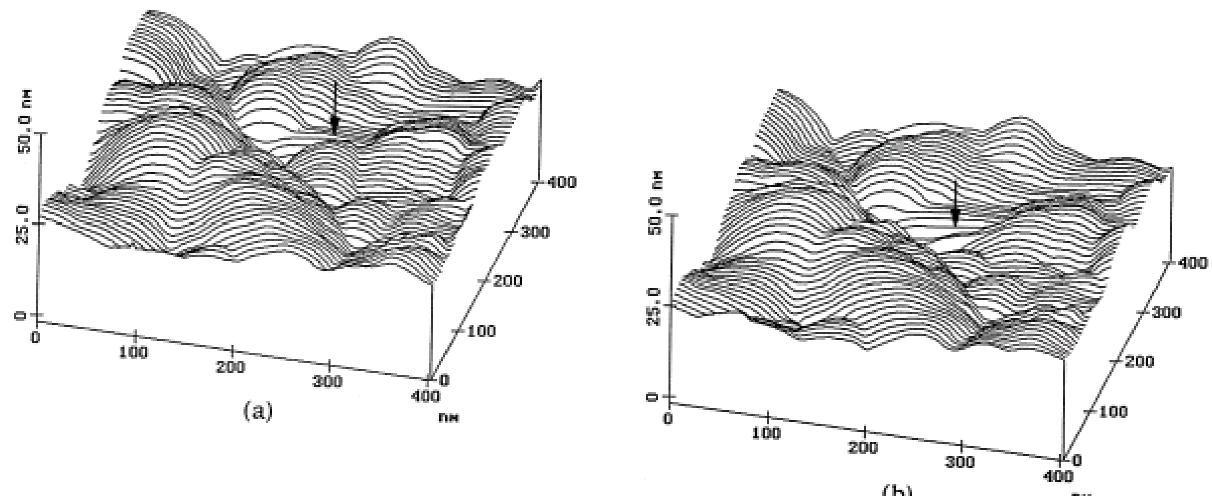
three-sided pyramidal single-crystal natural diamond tip with an apex angle of 80 degrees and a radius of about 100 nm mounted on a stainless steel cantilever beam with normal stiffness of about 25 N/m is used at relatively higher loads (1 microN-150 microN). For scratching and wear studies, the sample is generally scanned in a direction orthogonal to the long axis of the cantilever beam (typically at a rate of 0.5 Hz) so that friction can be measured during scratching and wear. The tip is mounted on the beam such that one of its edges is orthogonal to the long axis of the beam; therefore, wear during scanning along the beam axis is higher (about 2X to 3X) than that during scanning orthogonal to the beam axis. For wear studies, typically an area of 2 micromX2 microm is scanned at various normal loads (ranging from 1 to 100 mN) for a selected number of cycles. Nanofabrication/nanomachining is conducted by scratching the sample surface with a diamond tip at specified locations and scratching angles. The normal load used for scratching`(writing)`is on the order of 1-100 mN with a writing speed on the order of 0.1-200 mm/s.



Spiral pattern by nanofabrication



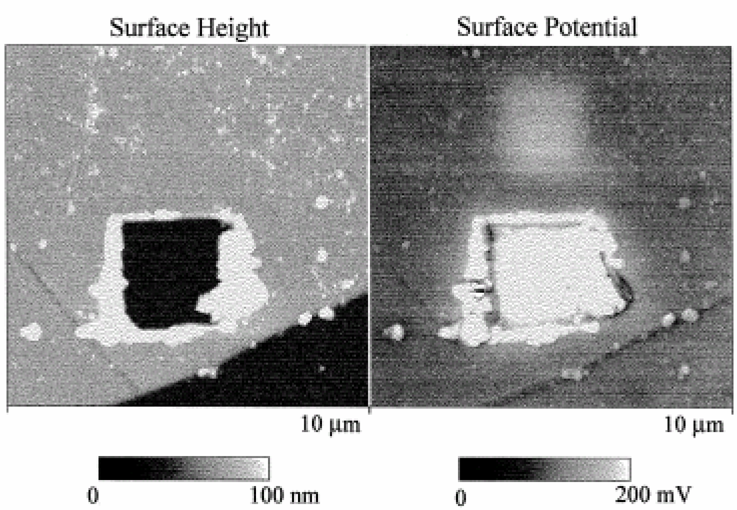
Scratch analysis as a function of different loads



Before Wear *After Wear (See Marked area)*

Surface potential measurements

To detect wear precursors and to study the early stages of localized wear, the multimode AFM can be used to measure the potential difference between the tip and the sample by applying a DC bias potential and an oscillating (AC) potential to a conducting tip over a grounded substrate in a so-called 'nano-Kelvin probe' technique. Mapping of the surface potential is made in the so-called 'lift mode'. These measurements are made simultaneously with the topography scan in the



tapping mode, using an electrically-conducting (nickel-coated single- crystal silicon) tip. After each line of the topography scan is completed, the feedback loop controlling the vertical piezo is turned off, and the tip is lifted from the surface and traced over the same topography at a constant distance of 100 nm. During the lift mode, a DC bias potential and an oscillating potential (3-7 V) is applied to the tip. The frequency of oscillation is chosen to be equal to the resonant frequency of the cantilever (80 kHz). When a DC bias potential equal to the surface potential of the sample (on the order of "2 V) is applied to the tip, it does not vibrate. During scanning, a difference between the DC bias potential applied to the tip and the potential of the surface will create DC electric fields that interact with the oscillating charges (as a result of the AC potential) causing the cantilever to oscillate at its resonant frequency, as in tapping mode. However, a feedback loop is used to adjust the DC bias on the tip to exactly nullify the electric field, and thus the vibrations of the cantilever. The required bias voltage follows the localized potential of the surface. Surface and subsurface changes of structure and/or chemistry can cause changes in the measured potential of a surface. Thus, mapping of the surface potential after sliding can be used for detecting wear precursors and studying the early stages of localized wear.

Nanoindentation measurements

For nanoindentation hardness measurements the scan size is set to zero and then a normal load is applied to make the indents using the diamond tip. During this procedure, the tip is continuously pressed against the sample surface for about two seconds at various indentation loads. The sample surface is scanned before and after the scratching, wear or indentation to obtain the initial and the final surface topography, at a low normal load of about 0.3 mN using the same diamond tip. An area larger than the indentation region is scanned to observe the indentation marks. Nanohardness is calculated by dividing the indentation load by the projected residual area of the indents. Direct imaging of the indent allows one to quantify piling up of ductile material around the indenter. However, it becomes difficult to identify the boundary of the indentation mark with great accuracy. This makes the direct measurement of contact area somewhat inaccurate. A technique with the dual capability of depth-sensing as well as in situ imaging which is most appropriate in nanomechanical property studies, is used for accurate measurement of hardness with shallow depths. This indentation system is used to make load-displacement measurement and subsequently carry out in situ imaging of the indent, if required. The indentation system consists of a three-plate transducer with electrostatic actuation hardware used for direct application of normal load and a capacitive sensor used for measurement of vertical displacement. The AFM head is replaced with this transducer assembly while the specimen is mounted on the PZT scanner which remains stationary during indentation experiments. Indent area and consequently hardness value can be obtained from the load-displacement data. The Young's modulus of elasticity is obtained from the slope of the unloading curve. Indentation experiments provide a single-point measurement of the Young's modulus of elasticity calculated from the slope of the indentation curve during unloading. Localized surface elasticity maps can be obtained using a force modulation technique. An oscillating tip is scanned over the sample surface in contact under steady and oscillating load. The oscillations are applied to the cantilever substrate with a bimorph. For measurements, an etched silicon tip is first brought in contact with a sample under a static load of 50-300 nN. In addition to the static load applied by the sample piezo, a small oscillating (modulating) load is applied by a bimorph, generally at a frequency (about 8 kHz) far below that of the natural resonance of the cantilever (70-400 kHz). When the tip is brought in contact with the sample, the surface resists the oscillations of the tip, and the cantilever deflects. Under the same applied load, a stiff area on the sample would deform less than a soft one; i.e., stiffer surfaces cause greater deflection amplitudes of the cantilever. The variations in the deflection amplitudes provide a measure of the relative stiffness of the surface. Contact analyses can be used to obtain a quantitative measure of localized elasticity of soft surfaces. The elasticity data are collected simultaneously with the surface height data using a so-called negative lift mode technique. In this mode each scan line of each topography image (obtained in tapping mode) is replaced with the tapping action disabled and with the tip lowered into steady contact with the surface.

Boundary lubrication measurements

The classical approach to lubrication uses freely supported multimolecular layers of liquid lubricants. The liquid lubricants are sometimes chemically bonded to improve their wear resistance. To study depletion of boundary layers, the micro-scale friction measurements are made as a function of number of cycles. Also the force-distance (between the probe and the surface) curve obtained from AFM measuments, one can directly get the thickness of the lubricating film and also an indication of its density. For nanoscale boundary lubrication studies, the samples are typically scanned using a Si3N4 tip over an area of 1 micro mmX1 micro mm at a normal load of about 300 nN, in a direction orthogonal to the long axis of the cantilever beam. The samples are generally scanned with a scan rate of 1 Hz and a scanning speed of 2 mm/s. Coefficient of friction is monitored during scanning for a desired number of cycles. After a scanning test, a larger area of 2 mmX2 mm is scanned at a normal load of 40 nN to observe any wear scar.

Today most of the research on nanotribology uses the AFM, and reseach groups have reported some highly interesting results. Some of them have been listed below.

<u>Some important results regarding the study of Nanotribology with the AFM</u>

Friction and Adhesion

(1) atomic scale friction force has been found to exhibit the same periodicity as that of the corresponding topography, with the peaks of both displaced relative to each other.

(2) There are Fourier expansions to convert the interatomic potential obtained from the machine into interatomic forces between the atoms of the FFM tip and that of the surface.

(3) However, maxima in the interatomic forces in the normal and lateral direction do not occur at the same location, which explains the observed shift between peaks in the lateral force and those in the corresponding topography.

(4) Coefficient of friction in regions that are not smooth is higher. Hence friction force values vary from point to point in the scan.

(5) the difference in the friction can also be because of planes oriented differently of because of presence of different phases.

(6) Using this property, FFM can also be used to map chemical variations, e.g., by using FFM with a modified probe tip, so that more pronounced interactions and hence a larger variation in the friction force due to them (called chemical force microscopy of CFM)

(7)Actually, variations in the micro scale friction depends on the variations in slope of the local surface, rather than the surface height distribution. (see Fig.10)
Friction force is high at places with positive slope and low at those having negative slope. A numerical explanation for this is given below:

(8) For small contact areas

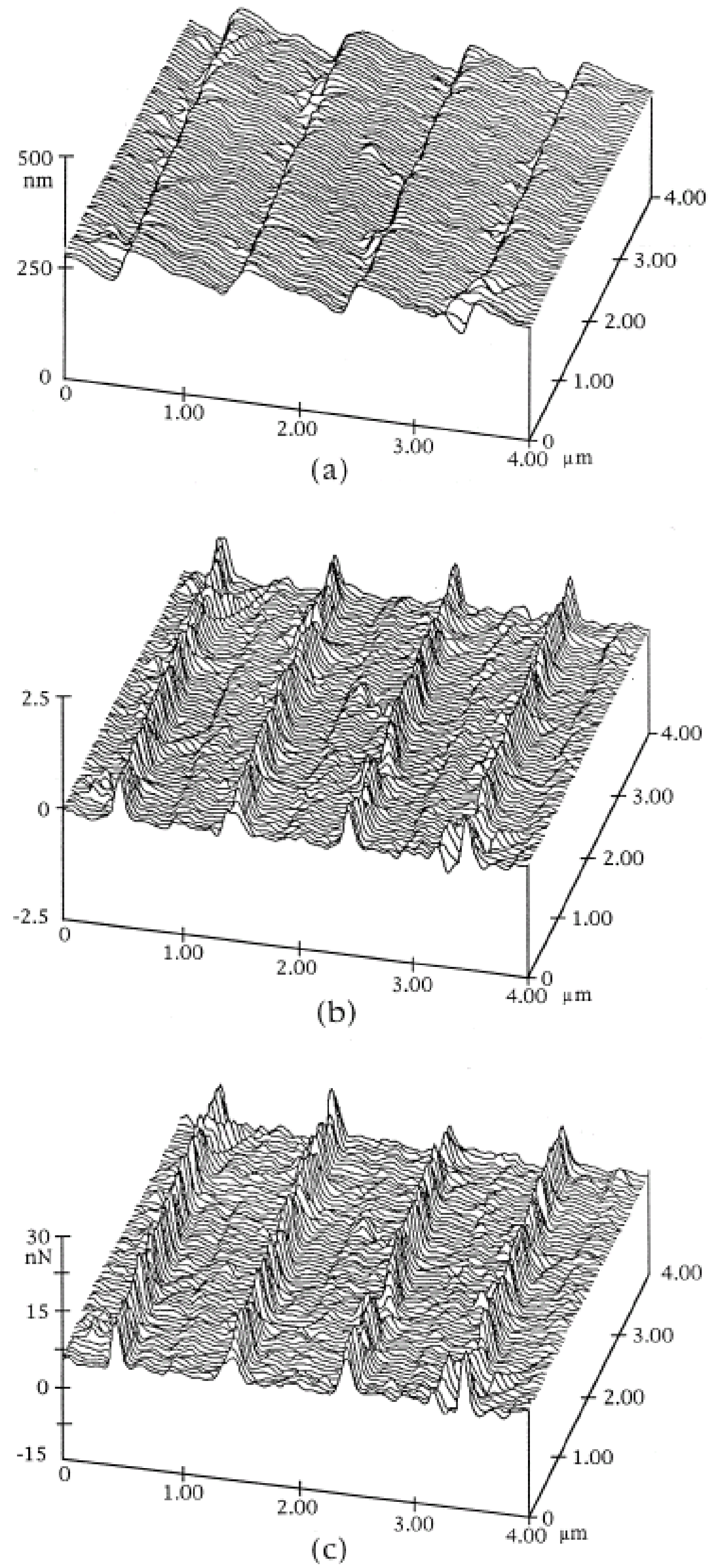


Fig. 10. (a) Surface roughness map, (b) surface slope map taken in the sample sliding direction (the horizontal axis), and (c) friction force map for a gold-coated ruling at a normal load of 155 nN [3].

and very low loads, used in microscale studies, indentation hardness and the modulus of elasticity are higher than the macroscale measurements.

(9) The coefficient of friction values on the microscale are much lower than that on the macroscale. A few reasons justifying this are:

(a) Contact stresses at the AFM conditions generally do not exceed the sample hardness which minimizes plastic deformation.

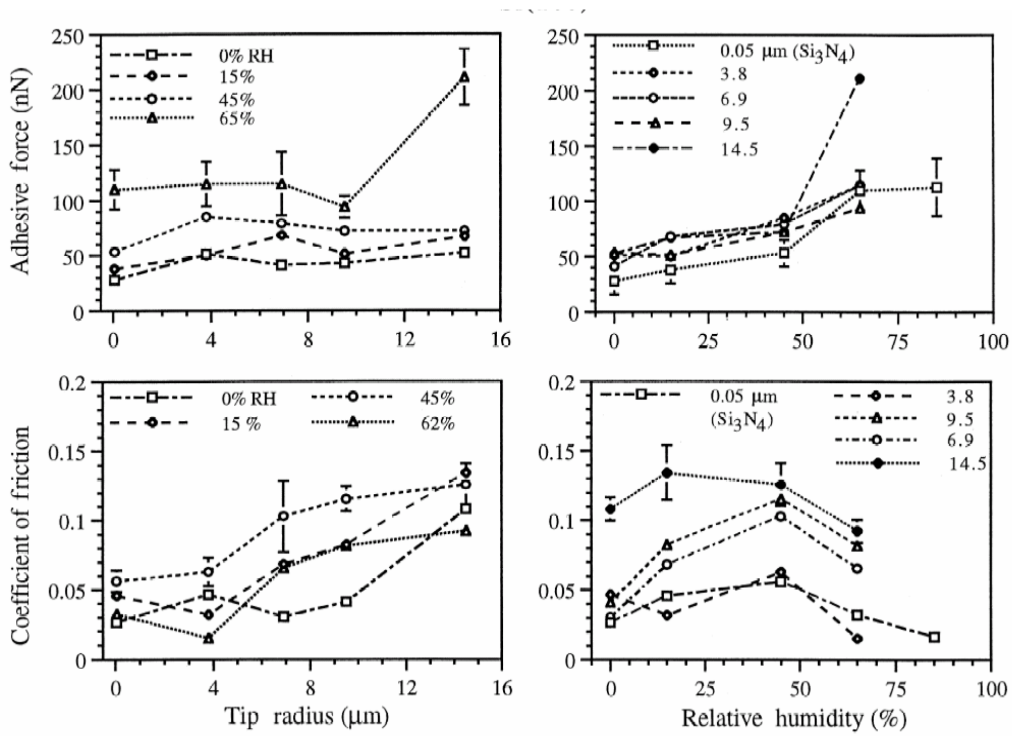
(b) Lack of plastic deformation and improved mechanical properties reduce the degree of wear and friction.

(c) Small apparent areas of contact lead to a smaller contribution from ploughing friction.

(10) Coefficient of friction increases with an increase in tip radius (large for macro scale measurements)

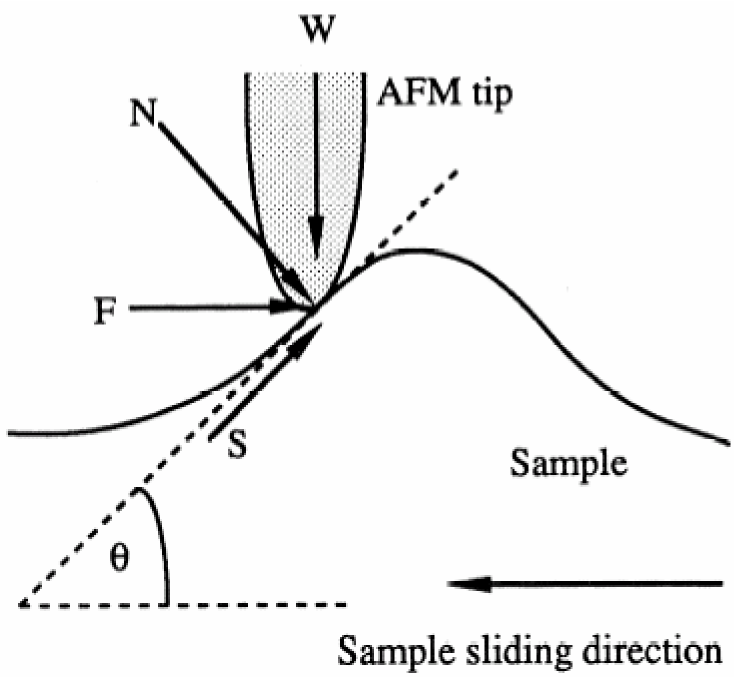
(11) The coefficient of friction for the microscale measurements increases with increase in the applied load. However according to Amonton's law, it is independent at the macro scale. Thus, micro scale sliding under lightly loaded conditions should experience ultra-low friction and near zero wear.

(12) For micro tips, there is no appreciable variation in adhesive force with the tip radius at a given humidity up to ambient humidity. The adhesion force increases as the relative humidity increases for all tips. This is because of the presence of meniscus forces, which arises from capillary condensation of water vapor from the environment forming meniscus bridges. If enough liquid is present to form a meniscus bridge, then the meniscus force should increase with increase in tip radius and should be independent of relative humidity or water film thickness. An increase in the tip radius in a dry environment results in increased contact area, therefore higher van der Wall's forces. If nanoasperities on the tip and the sample are considered, then the number of the contacting and near contacting asperities forming meniscus bridges increases with the increase in humidity. Therefore the tip radius has little effect on the adhesive forces at low humidities but increases with tip radius at high humidities. Adhesive force also increases for an increase in humidity for all tips. This observation suggests that the thickness of the liquid film at low humidities is insufficient to form continuous meniscus bridges to effect adhesive forces, in the case of all tips.
Coefficient of friction increases with tip radius. This increase at low to moderate humidities arises from increased contact area (higher van der Wall's forces) and higher values of shear forces. At high humidities, similar to adhesive force data, an increase with tip occurs due to both contact area and meniscus effects. However, AFM/FFM only measures the combined effect.



Coefficient of friction increases with humidity till ambient values, beyond which it starts to decrease. The initial increase is because of water film increase which results in a larger number of the nanoasperities forming meniscus bridges. But beyond 65% relative humidity, the absorbed water film acts as a lubricant.

(13) the local friction force on a micro scale is different as the scanning direction of the sample is reversed. This is because the asperities on the sample surface are unsymmetrical and also because of some material transfer to one side of the asperities. Hence, if the asperities are all in a preferential direction then this effect of scanning direction is also felt on the macro scale friction measurements. A mathematical model for this has been provided by Dr. Bharat Bhushan:



The FFM measures the lateral force F. If u is the local coefficient of friction then: u = S / N. The friction coefficient measure using the machine, is the lateral force by the normal force, i.e. u(measured) = F / W. Calculate F for

the cases of climbing up and down the asperity by balancing forces, we get
u (measures, moving up) = (u + tan (theta)) / (1 - u.tan(theta)) ~ u + tan(theta)
u (measured, moving down) = (u - tan(theta)) / (1+u.tan(theta)) ~ u - tan(theta).
Therefore going up one part on the surface gives a different friction force measurement from that measured while coming down the same part.
Note: This effect is felt at the nanoscale. However if all the asperities are preferentially aligned, then this anisotropy is felt at the macro scale too (like a hacksaw blade).

Identifying materials with low friction and good adhesion for nanotechnology applications:

Recently it has been shown that the friction coefficient is almost inversely proportional to the Young's modulus, for low scan speeds. However for higher scan speeds, the coefficient of friction has been found to be higher for materials with higher modulus of elasticity. Therefore if our application involves high speeds, we use materials with low stiffness (low E), while during low speed applications, we prefer materials with high elasticity modulii.

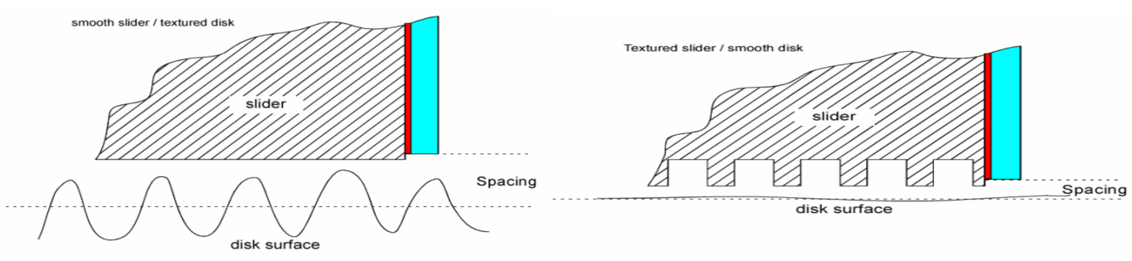
Applications of nanotribolgy in current products:

(1) **Ultra low flying head disks interfaces**

For extremely high density recording , spacing (fly-height) is expected to be reduced further. It is estimated that in order to achieve a recording density of 100 Gb/in2, the flying height would have to be about 6 to 7 nm. The tribological issues encountered for such low flying heights are enormous. One of the major challenges faced at such low heights is that of avoiding contact. For this purpose ultra smooth surface would have to be used. Also on ultra smooth surfaces the adhesive/intermolecular forces play an important role
Fly-height on modern hard disk drives is around 20-30nm, areal densities is around 9Gb/in2. At such flying heights the air bearing force balances the pre-load and adhesion forces between the surfaces is insignificant. But as we reduce the fly-height adhesion forces become significant. It has been shown that the adhesion forces may dominate the forces at interface for smoother surfaces and thicker lubricants at the surfaces (including humidity)
We can have two different cases at low fly-heights:

1. If adhesion force Fs = 0, then F = Fa (air-bearing force) assuming contact force to be negligible
2. If Fs is not equal to zero, then for large adhesion forces the interfaces will collapse.

Also as fly-height decreases asperity contact may or may not occur. This suggests that roughness of the disk must be reduced. However as mentioned above, a very smooth surface is unwanted because of increased adhesion between head and disk which can lead to a failure of head on disk. In order to reduce stiction forces in case of smooth disks a textured slider surface has been suggested and investigated.



It has been shown that slider surface texture is effective to reduce friction, stiction, and contact-induced vibration of air-bearing modes in the near-contact regime.

(2) **Nanolubrication**

Lubrication has been based on two main principles – Generation of fluid pressure to separate the surfaces to avoid contact; Easily sheared chemical films formed on the surface to redistribute the stresses and sacrificially worn off, to protect the surface. Lubrication at nanoscale requires lubricant molecules which are non-volatile, oxidation and temperature resistant, good adhesion and cohesion and self repairing or self regenerating. This leads to an all organic film, if an organic film can stay in tact under the application of forces and repair by itself.

The wear resistance of monomolecular film can be related directly to the bonding strength and cohesive strength of the monolayer. The famous Langmuir-Blogett films behave like solids, i.e. a solid will deform under contact stress. These solid films produce defects on application of stress which will eventually lead to failure. The durability of such films under constant contact is very less. How to make a layer last long?

This can be done by introducing self repairing self generating property which is defined as the ability of molecules to rearrange themselves into the original state after they have been disrupted by a contact. This necessarily means that the molecules should have a high mobility. But high mobility implies that the molecules cannot be chemically bonded to the surface. Hence, it has low bonding strength. Therefore we have a contradicting phenomenon of strong adhesive force and self-reparability. The solution to this situation is to have a mixed molecular structure in which one type of molecule bonds chemically and the other species are allowed to on freely on the surface.

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