Atomic Force Microscopy for
NanoTribology Applications:

The term tribology is derived from the Greek word "tribo" meaning rubbing and "logy" meaning knowledge. The original applications by the Greeks of tribology were in trying to understand the motion of large stones across the earth's surface. Today tribology has grown to include the methodical study of friction, lubrication, and wear.

Tribology plays a critical role in diverse technological areas. In the advanced technological industries of semiconductor and data storage, tribological studies help optimize polishing processes and lubrication of data storage substrates. In traditional industries such as automotive and aerospace, tribological studies help increase the lifespan of mechanical components.

Many industrial processes require a detailed understanding of tribology at the nanometer scale. The development of lubricants in the automobile industry depends on the adhesion of nanometer layers (mono layers) to a material surface. Assembly of components can depend critically on the adhesion of materials at the nanometer length scale.

There are a number of traditional tools for characterizing friction, lubrication and wear. The most common characterization tool is the tribometer having several configurations such as pin-on-disk, ball on flat, and flat on flat, etc. Generating motions at the nanometer scale is extremely challenging. New characterization techniques are required to understand tribology at the nanometer scale.

The atomic force microscope is now being routinely applied for studying nanoscale tribology. The natural extension of the AFM for tribology applications is derived from the motion of a nanometer-sized stylus in the AFM over a surface. Although traditional tribology testing is not done with an AFM, many new types of applications are possible.

Examples of the application of AFM to tribology include:

- Direct three-dimensional visualization of wear tracks, or scars on a surface.
- Measurement of the thickness of solid and liquid lubricants having nanometer or even monolayer thickness.
- Measurement of frictional forces at the nanometer scale.
- Surface characterization of morphology, texture,and roughness.
- Evaluation of mechanical properties such as hardness and elasticity, and plastic deformation at the nanometer scale.

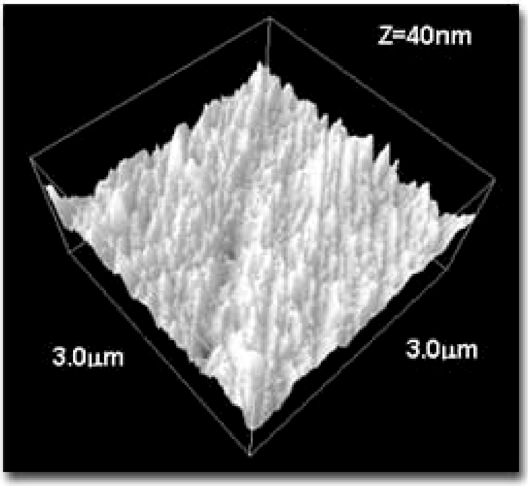
A major advantage of the AFM for tribological studies is that the AFM can be routinely used on all types of materials. Materials commonly studied include: ceramics, metals, polymers, semiconductors, magnetic, optical, and biomaterials. AFM investigations are usually made in ambient air environment. It is possible to make AFM studies in a vacuum or liquid environment.

Nanoscale Wear Analysis

The effects of wear at the nanometer scale become critical to the optimization and stability of machines as the tolerances in precision machines become smaller and smaller. Traditional microscopes such as the optical and scanning electron microscopes facilitate visualization of wear in 2-dimensions. For example, with the SEM it is possible to get a magnified view of wear tracks in the x-y axis but cross sectioning is required for measuring the depth of wear tracks.

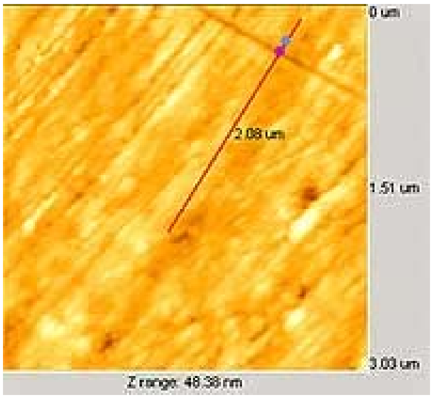
The AFM allows direct 3-dimensional visualization of wear tracks and scars. The images may be displayed in a 2-D projection and a 3-D projection. Direct measure of wear track depth can be easily measured with a line profile derived from the AFM image.

Figure 1

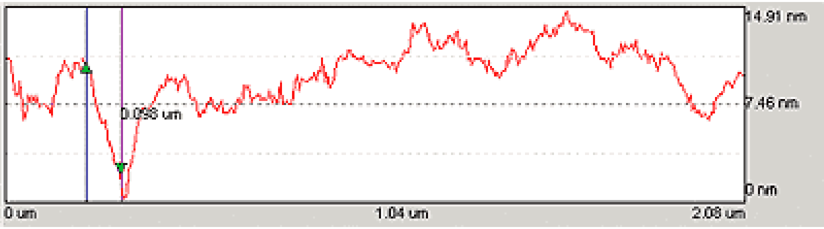


Three-dimensional atomic force microscope (AFM) image of a polish mark on a piece of steel. The scan range in X and Y is 3 micrometers and the entire Z range is 40 nanometers.

Figure 2



Metrological study of a scratch mark in the surface of a polished material (stainless steel). Because the AFM directly measures three-dimensional data, the depth of the scratch mark is easily quantified. In this case the mark is 8.6 nm deep. Z= 8.6 nm



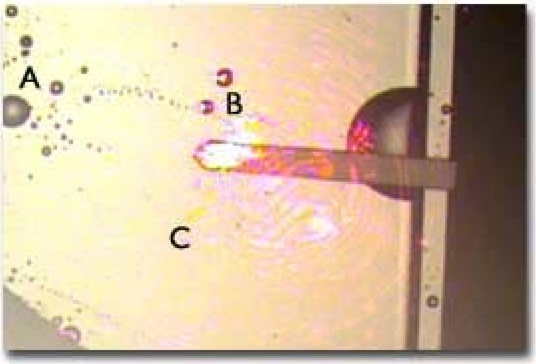
Lubricant Studies

It is well known that layers of lubricants on surfaces that are less than 100 nm can dramatically affect lubrication behavior. Characterization of such films is necessary for developing optimized lubricating films. However, nanometer scale characterization of lubrication films offers a substantial challenge. Optical techniques such ellipsometers can be used for measuring lubrication thickness of large sections, (greater than 10 square micrometers), of a surface. Measurement of the localized (less than 1 micron) film thickness is not possible with the ellipsometer.

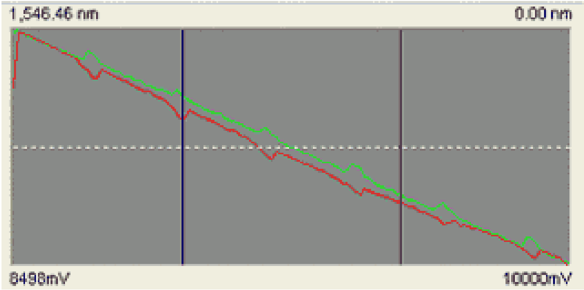
The probe is mounted at the end of a cantilever in an AFM making it possible to measure interaction forces between the probe and the surface by monitoring the deflection of the cantilever. A graph, called a force/distance curve, shows the forces on the probe as the distance between the probe and the surface are reduced. The nature of the force/distance curve depends on the force constant of the cantilever, the lubrication density, probe geometry, and the lubrication thickness.

By measuring the changes in force/distance curves in an AFM it is possible to directly ascertain the thickness of lubrication films. Below is an example of a force/distance curve for a surface with no lubrication film compared to one with a lubrication film. The thickness of the film is established from the force/distance curve.

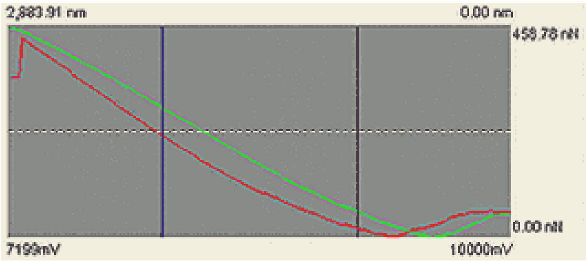
Figure 3



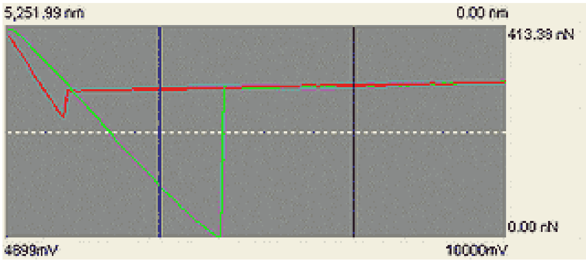
Video optical microscope image of a silicon surface coated with a lubricant. Force/Position curves were measured at locations on the surface indicated with the letters A, B, and C.



A: *Force/Position curve measured on one of the droplets of lubricant. The slope represents the force required to move the AFM probe through the liquid surface.*



B: *Force/Position curve at a place on the surface where there is apparently a thin film of lubricant material.*



C: *Force/Position curve on a section of the silicon surface that appears to have no lubrication.*

Frictional Forces

Friction between two surfaces depends on the chemical and mechanical interaction between the surfaces. Changes in chemical composition giving rise to friction are measurable with the AFM. The technique for measuring these forces is called lateral force, or frictional force microscopy.

As the probe moves over a surface in the AFM, changes in the chemical composition of the surface can give rise to torsions of the cantilever on which the probe is mounted. The torsion of the cantilever is then proportional to the friction between the probe and the surface.

Figure 4

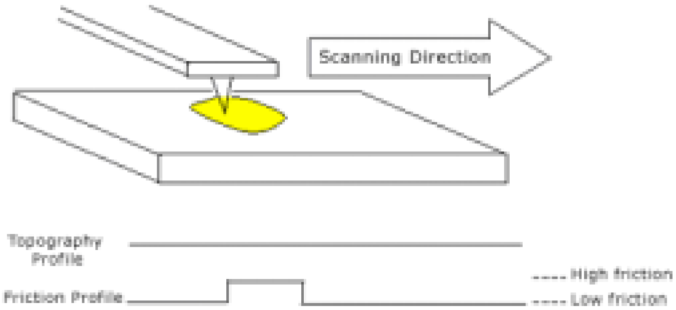
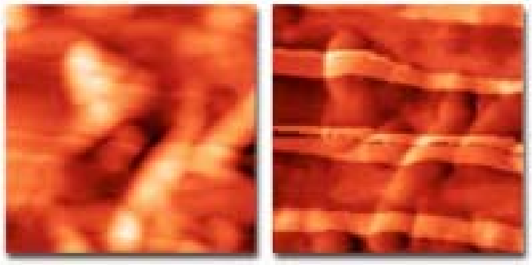


Illustration of the principle that allows lateral force or frictional fore microscope images to be measured. The cantilever will twist as the probe interacts with the surface while scanning.

In an AFM it is possible to simultaneously measure topography and frictional force images. The topography image is derived from monitoring the vertical forces on the cantilever. The friction image is acquired simultaneously by monitoring the lateral motions of the cantilever. Below is a FFM image of a sample illustrating changes in the friction.

Figure 5

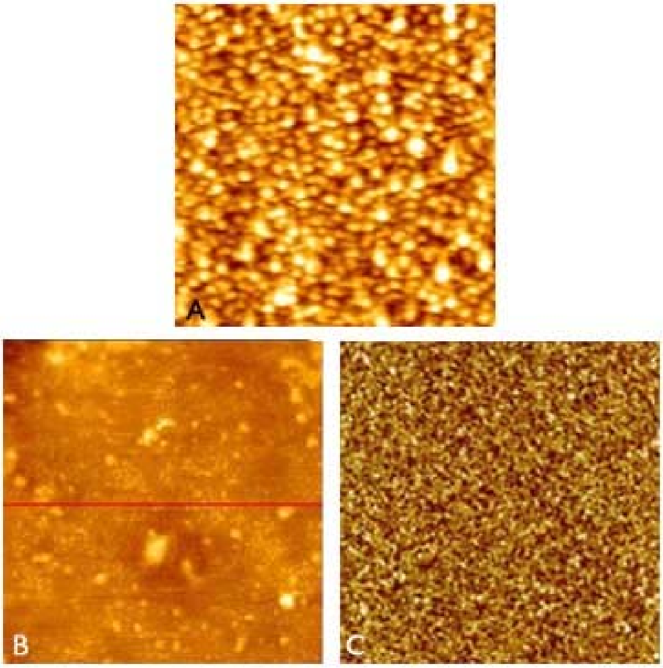


(left) Two dimensional view of a composite material measured with the AFM. Barely visible in this image are striation marks derived from a change in chemical composition at the surface.(right) The lateral force or frictional force image of the composite material clearly shows changes in chemical composition at the surface of the composite material. Both the topography and frictional force image are measured simultaneously with the AFM.

Surface Texture/Morphology/Roughness

The AFM gives extremely high contrast on surfaces that are flat at the nanometer scale. Optical and electron microscopes are not able to resolve surface texture that is easily measured with the AFM. Applications include the visualization of surface topography in both 2-d and 3-d perspectives, line roughness measurements, and area roughness measurements. All of the traditional area and surface roughness parameters can be calculated after the AFM image is acquired.

Figure 6



Ra:	0.71 nm	**Sa**:	0.157 nm
Rq:	0.90 nm	**Sq**:	0.197 nm
Rsk:	.45 nm	**Ssk**:	0.0119 nm
Rku:	3.67	**Sku**:	2.29
Rz:	4.63 nm	**Sz**:	1.38 nm

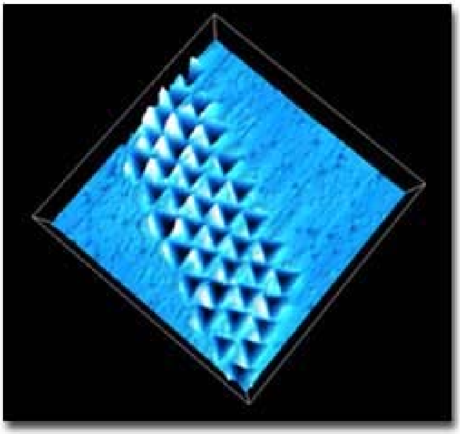
(A) AFM image of a metal bonding pad on a semiconductor device (B) Use of the AFM to measure line roughness of a polymer sample (C) AFM image of polished silicon and the area roughness of the silicon.

Nanoscale Mechanical Properties

Mechanical properties such as hardness, elastic modulus, stiffness and compressibility as well as material behavior such as plastic deformation, and fracture can be studied with the AFM.

It is possible to study nano-hardness by directly pressing an AFM probe into a sample's surface; however, it is advantageous to use an instrument that is optimized for nano-indentation. The primary advantage of the nano-indenter over an AFM for nano-hardness measurements is that it is easier to get calibrated measurements with the nano-indenter. It is useful to use the AFM to measure the three-dimensional topography of indentations made with a nano-indenter. AFM images allow direct visualization of material deformation or fracture behavior.

Figure 7



Three-dimensional view of nano-indents in a material surface. From the AFM image it is possible to see the depth of the indentation as will as visualizing the material deformation.

Using techniques such as pulsed force mode, the stiffness of a sample at a matrix of locations is measurable. From this data it is possible to create a stiffness mapping of a surface. Stiffness maps can only be made on samples where the stiffness of the surface is lower than the stiffness of the cantilever. Such stiffness images are routinely measured on polymer samples.

Adding a fixture to the stage of the AFM makes the study of material behavior such as plastic deformation and fracture possible. The fixture permits creating forces on a sample while AFM images are being taken. A variety of materials may be studied with such a technique.

Acknowledgment
This article was written with the assistance of Dr. Hong Liang. Dr Liang is an Assistant Professor in the Mechanical Engineering Department at the University of Alaska Fairbanks. Her specialty is the applicationof tribological studies to several areas of science and technology including surface properties of advanced materials and nanomanufacturing processes.