# Surface Roughness

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# INTRODUCTION

## Significance

Characterization of surface topography is important in applications involving friction, lubrication, and wear (Thomas, 1999). In general, it has been found that friction increases with average roughness. Roughness parameters are, therefore, important in applications such as automobile brake linings, floor surfaces, and tires. The effect of roughness on lubrication has also been studied to determine its impact on issues regarding lubrication of sliding surfaces, compliant surfaces, and roller bearing fatigue. Finally, some researchers have found a correlation between initial roughness of sliding surfaces and their wear rate. Such correlations have been used to predict failure time of contact surfaces.

Another area where surface roughness plays a critical role is contact resistance (Thomas, 1999). Thermal or electrical conduction between two surfaces in contact occurs only through certain regions. In the case of thermal conduction, for example, the heat flow lines are squeezed together at the areas of contact, which results in a distortion of the isothermal lines, as illustrated in Figure 1.

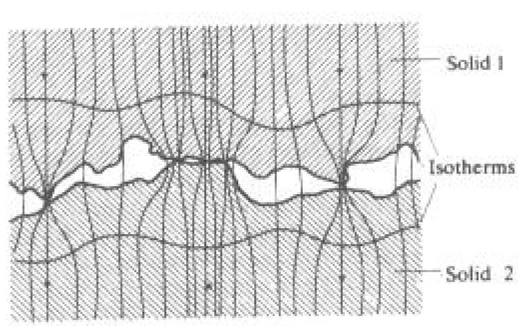


Figure 1. Contact Resistance Due to Constriction of Flow Lines (Thomas, 1999)

Thermal contact resistance is an important issue in space applications, such as satellites, where the heat generated by the electronic devices can only be driven away by conduction.

Surface roughness is also a topic of interest in fluid dynamics (Thomas, 1999). The roughness of the interior surface of pipes affects flow parameters, such as the Reynolds number, which is used to evaluate the flow regime (i.e., laminar or turbulent). The performance of ships is also affected by roughness in the form of skin friction, which can account for 80-90% of the total flow resistance. In addition, the power consumption can increase as much as 40% during the service life of a ship as a result of increased surface roughness caused by paint cracking, hull corrosion and fouling.

The examples mentioned above are just a few of the applications in which surface roughness has to be carefully considered. However, the influence of roughness extends to various engineering concerns such as noise and vibration control, dimensional tolerance, abrasive processes, bioengineering, and geomorphometry (Thomas, 1999).

**Definition and Parameters**

The concept of roughness is often described with terms such as ‘uneven’, ‘irregular’, ‘coarse in texture’, ‘broken by prominences’, and other similar ones (Thomas, 1999). Similar to some surface properties such as hardness, the value of surface roughness depends on the scale of measurement. In addition, the concept roughness has statistical implications as it considers factors such as sample size and sampling interval.

The characterization of surface roughness can be done in two principal planes (Thomas, 1999). Using a sinusoidal curve as a simplified model of the surface profile, roughness can be measured at right angles to the surface in terms of the wave amplitude, and parallel to the surface in terms of the surface wavelength.  The latter one is also recognized as texture.  The technique used to measure roughness in any of these two planes will inevitably have certain limitations.  The smallest amplitude and wavelength that the instrument can detect correspond to its vertical and horizontal resolution, respectively.  Similarly, the largest amplitude and wavelength that can be measured by the instrument are the vertical and horizontal range.

The first amplitude parameter used for roughness measurements was the vertical distance between the highest peak and the lowest valley of the unfiltered profile, $P_t$ (Thomas, 1999).  The designation of this parameter was subsequently changed to $R_t$ when electrical filters were incorporated.  This parameter was further divided into $R_p$ and $R_m$, as illustrated in Figure 2.

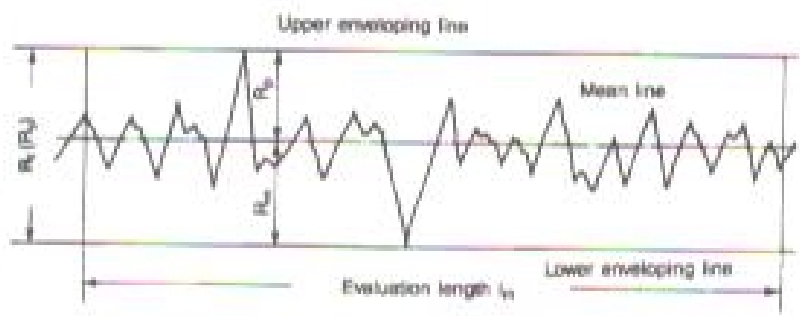


Figure 2.  Graphical Description of $R_t$, $R_p$, and $R_m$ (Thomas, 1999)

Since it was mentioned that the concept of roughness has statistical implications, the next step in the development of roughness parameters was to obtain an average parameter of roughness.  In the U.S., this was done by connecting an AC voltmeter to measure the root mean square (RMS) average of the electrical signal.  Thus, the RMS roughness was defined as follows:

$$R_q = \sqrt{\frac{1}{L}\int_0^L z^2(x)dx}$$

where,

L = evaluation length

z = height

x = distance along measurement

In Europe, the signal of the instrument was passed through a rectifier in order to charge up a capacitor. As a result, the output of the instrument was the center-line average (CLA) roughness:

$$R_a = \frac{1}{L}\int_0^L |z(x)|dx$$

The next step in the realization of the statistical nature of roughness was to consider the distribution of heights *p(z)*, as shown in Figure 3.

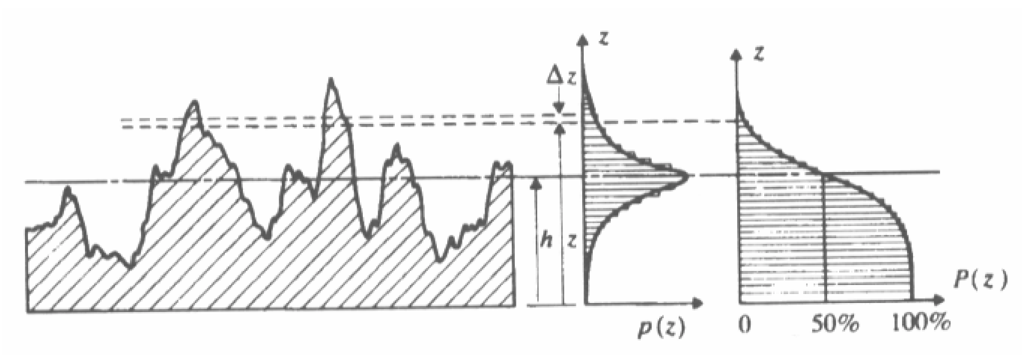


Figure 3. Profile Height Distribution *p(z)* (Thomas, 1999)

The parameters used to characterize such distributions were the central moments, defined by the following expression.

$$\mu_n = \int_{-\infty}^{\infty} z^n p(z)dz$$

The second moment $\mu_2$ is known as the *variance* and represents the deviation of the distribution from its mean. Taking the square root of the variance results in the standard deviation $\sigma$, which is numerically identical to the RMS roughness. The third moment $\mu_3$ is the *skewness* and is a measure of the asymmetry of the distribution. Finally, the fourth moment $\mu_4$ is known as the *kurtosis* and represents the shape of the distribution curve.

In addition to amplitude parameters, there are other parameters that are used to characterize texture. One of them is the high-spot count (HSC), which is the number of peaks per unit length. Its reciprocal, $S_m$, is the mean spacing between peaks. Another parameter used to evaluate texture is the profile length ratio $R_L$, which is the length of the profile divided by its nominal length. Other parameters found in the literature have not received popular acceptance (Thomas, 1999).

## MEASURMENT TECHNIQUES

### Stylus Instruments

Stylus instruments are based on the principle of running a probe across a surface in order to detect variations in height as a function of distance (Thomas, 1999). One of the early stylus instruments employed a system of levers to magnify the vertical displacement of the stylus and recorded the profile on a smoked-glass plate. A schematic representation of this instrument is depicted in Figure 4.

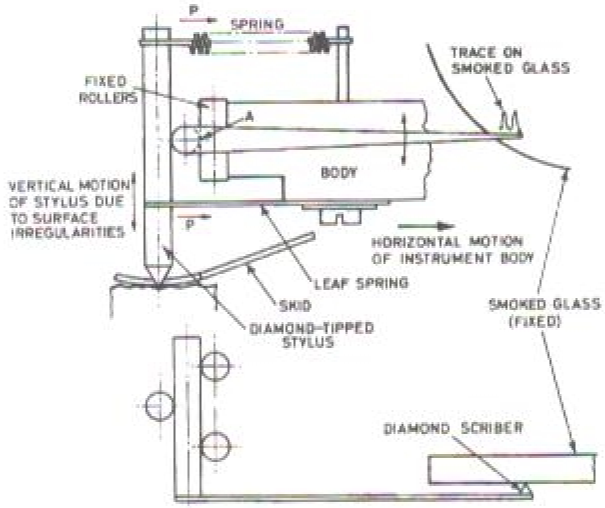


Figure 4. Tomlinson Roughness Meter (Thomas, 1999)

The next step in the development of the stylus instruments was to incorporate a transducer, which converted vertical displacement into an electrical signal. This signal can then be processed by the instrument electronics to calculate a suitable roughness parameter. The type of transducer used largely affects instrument performance. A piezoelectric crystal is often used as the transducer in the less expensive instruments. Other transducer mechanisms include moving coil transducers, capacitance transducers, and linear variable differential transformers (LVDT). The resolution of a stylus instrument depends on its manufacturer and model. The Tencor P2 (SP-P2), for instance, has a horizontal resolution of 0.02 μm, while the Tencor alpha-step 200 (SP-α200) has a horizontal resolution of 0.04 μm (Poon and Bhushan, 1995).

Some error can be introduced in roughness measurements when a stylus instrument is used because of several factors. Some of these factors are the size of the stylus, stylus load, stylus speed, and lateral deflection by asperities. The effect of stylus size is illustrated in Figure 5, which is a schematic comparison of an actual profile against the traced profile.

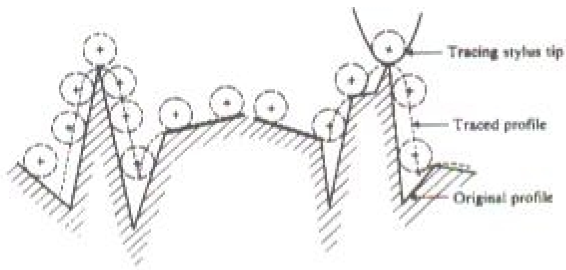


Figure 5. Distortion of a Surface Profile Due to the Effect of Stylus Size (Thomas, 1999)

This effect becomes more significant as the curvature of the peaks and valleys decreases, or the magnitude of the slope increases (Thomas, 1999).

Regarding the effect of stylus load, it has been found that plastic deformation can be induced on the surface if a load much higher than the recommended by the standards is used (Thomas, 1999). It has been argued, however, that if plastic deformation occurs by the same magnitude everywhere along the segment measured, the profile obtained is still representative of the original surface. One study showed that profile measurements across the same segment under different loads resulted in very similar profiles. The profiles obtained are presented in Figure 6.


Figure 6. Effect of Stylus Load (Thomas, 1999): (a) Profile at 6 mg load; (b) Relocated Profile at 80 mg Load; (c) Relocated Profile at 6 mg Load Again

Another way in which measurement errors can happen is if the stylus loses contact with the surface as a result of its speed (Thomas, 1999). Nevertheless, it was found that, for most surfaces, the errors introduced by the stylus speed were minor. Lateral deflection of the stylus has also been considered as a source of error. The effect of lateral deflection on profile measurement was also determined to be inconsequential when compared to the dimensions of the stylus.

**Optical Instruments**

A beam of electromagnetic radiation can be reflected off a surface in three different ways: specularly, diffusely, or both (Thomas, 1999). This is illustrated in Figure 7.

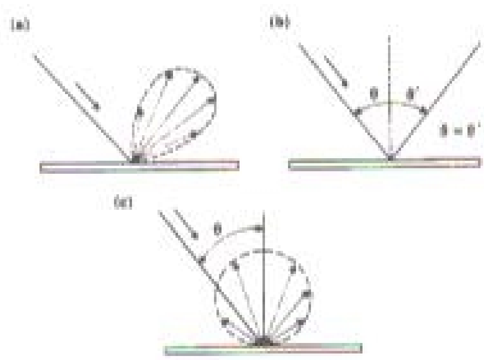


Figure 7. Modes of Reflection (Thomas, 1999): (a) Combined Specular and Diffuse; (b) Specular Only; (c) Diffuse Only

Depending on the surface roughness, radiation of a certain wavelength may be reflected specularly, while radiation of another wavelength may be reflected diffusely. Thus, the amount of specular and diffuse reflection can be used to determine surface roughness.

One instrument that employs specular reflection to characterize roughness is the light-section microscope (Thomas, 1999). An image of a slit is projected onto the surface and the objective lens captures the image at the specular reflection angle. If the surface is smooth, the image obtained will be straight; however, if the surface is rough, an undulating pattern will be observed. This instrument is suitable to measure peak-to-valley roughness with a vertical resolution of about 0.5 μm. Its principle of detection is illustrated in Figure 8.

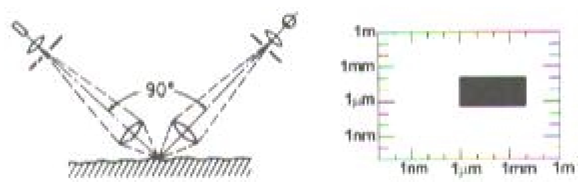


Figure 8. Principle of Light-section Microscope (Thomas, 1999)

The interaction of polarized light with a surface can also be employed to evaluate surface roughness. Such is the case of the long-pathlength optical profiler, which focuses a laser beam onto a surface by means of an arrangement of mirrors (Thomas, 1999). Before reaching the specimen, the laser goes through a Wollaston prism that polarizes the beam into two orthogonal components. The beams are then focused onto the surface where they reflect back to the prism. Finally, the reflected beams are directed to a beamsplitter, which sends each beam to a different detector. The phase difference of the polarized beams, which is related to the height difference at the surface, results in a voltage difference that can be measured. This instrument was reported to have a vertical range and resolution of 2 μm and 0.025 nm, respectively. A schematic diagram of the instrument is shown in Figure 9.

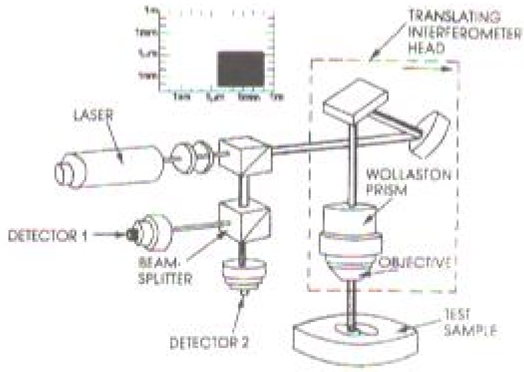


Figure 9. Long-pathlength Optical Profiler (Thomas, 1999)

Commercial instruments that measure the intensity of specular reflection are known as glossmeters (Thomas, 1999). The ability of these instruments to measure roughness is based on the inverse correlation between the intensity of specular reflection and the RMS roughness. One major advantage of this technique is that it allows for quick inspection of similar surfaces. The vertical resolution of a glossmeter is about 1 nm. It has been found, however, that roughness measurements using this technique do not correlate very well with stylus measurements. As a result, the instrument readings must me normalized for each type of material that is examined.

Ellipsometry is another technique that has been used for surface characterization (Thomas, 1999). It measures the change in polarization after a beam of light is reflected from a surface. The use of ellipsometry to measure roughness is still under investigation because the amount of beam rotation is also affected by other surface factors such as composition, temperature, strain state, etc.

**Microscopy Background**

The microscopy process began in the 15th century where the first magnifying glass was used. The first simple microscopes were used to view simple objects and organisms such as cells and bacteria. The resolution of the viewed objects was very limited at first due to the value of the wavelength of visible light spectrum. The shortest wavelength of visible light is 0.4micrometers and the resolution of the best microscopes is only 0.2 micrometers. Due to this limitation, a need for more improved and enhanced techniques to go beyond just the visible light spectrum was needed (Bai, 1999).

Along with the discovery of the atom and following that nature of particles extensive experimentation led to the discovery of how electrons behave. In 1931 E. Ruska and M. Knoll invented the first ever electron microscope taking us beyond the visible light spectrum. Since 1931 we have developed many types of microscopy instruments that have surpassed the first electron microscope and have greatly enhanced our way of life.

In the search to further understand the atomic structure of materials the resolution of the instrument needed to expand laterally also. Scanning Electron Microscopes or SEM has the smallest cross sectional area for the probe but did not encompass a large enough lateral scale. They also were unable to resolve any atomic structures during a test. Other difficulties arose, as other techniques were developed. Some of these difficulties were: poor resolution of surface structures, complicated surface preparation and stability of against high electric fields. Due to the complications and difficulties of some of the older processes further mechanisms of testing needed inventing. In 1981 Zurich Research

Laboratory of the International Business Machines inverted the first scanning tunneling microscope.

This report will not contain information about every instrument of detection. The number of instruments of detection discussed in the microscopy section of this report will instead be limited. Some of the other instruments of detection that will not be discussed include: lateral force microscopy (LFM), magnetic force microscopy (MFM), ballistic-electron microscopy (BEM), Scanning-Ion Conductive Microscopy, Near-Field Scanning Optical Microscopy, Scanning Thermal Microscopy, Scanning Tunneling Potentiometry, Photon Scanning Thermal microscope, and Scanning Electron Microscopy.

**Scanning Tunneling Microscopy**

Scanning tunneling microscopy (STM) is different from most of the other microscopy processes because it does not use any lenses, special lighting or an electron source. STM instead uses the existing bound electrons on the specimen as a source of radiation. Using low bias voltage ($V_b$), tunneling current (I) is passed through potential barriers to a probing metal tip. The equation to describe the tunneling current is:

$$I \approx 18 \frac{V_b}{10^4 \times \Omega} \times \frac{k}{d} \times A_{eff} \times e^{-2dk}$$

$A_{eff}$ is the effective area of the probe tip which aids in the determining of the lateral resolution, where k is part of the average work function. If constant current is maintained to approximately ±2%, the gap d, between substrate and probe tip, will remain at a constant height above the surface (Bai 1999).

STM has the ability to work in two modes. Theses are: constant height mode and constant current mode. While operating in constant height mode the tip can be scanned rapidly across the surface maintaining a constant bias voltage. The feedback loop in the system continually adjusts and monitors the tunneling current. Any changes to the tunneling current are recorded along with the scan position are used to construct a final plot of the surface. Faster imaging of atomically flat surfaces is made possible through constant height mode due to the fact that the feedback loop and piezoelectric driver do not have to correct continually for any surface variations. As can be seen in the figure 10 below the probe tip maintains a constant height moving only in the x-y direction.

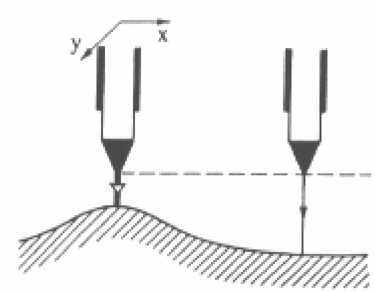


Figure 10. Constant Height Mode of STM (Bai, 1999)

In constant current mode the probe tip is scanned across the surface and the tunneling current is kept constant. The height of the probe tip is then continually adjusted by monitoring a feedback voltage ($V_f$). Once the probe tip has scanned the entire x-y plane surface a 3D surface is generated using the feedback voltage. Constant current mode is better adapted to monitor surfaces that are not atomically flat. In the case of constant current mode the feed back loop is used a great deal more than constant height mode causing the speed to be greatly hampered by the feedback loop. As can be seen in figure 11 below, the probe tip maintains a fixed distance above the substrate surface. In figure 12 we can see that the tip path outlined by the doted line represents the path traveled by the probe tip as it passes along and over each metal particle (Bai 1999).

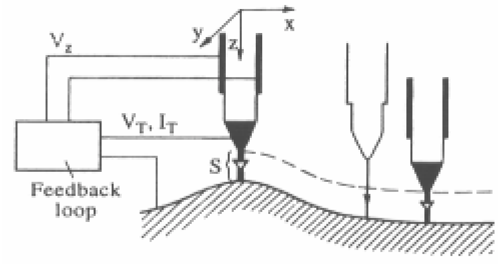


Figure 11.  Constant Current Mode (Bai, 1999)

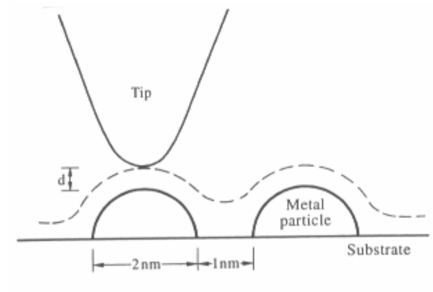


Figure12. Scanning Profile of STM (Bai, 1999)

The construction of the probe tip is also very important to the STM process. Probe tips are generally constructed from tungsten (W), platinum-iridium (Pt-Ir) or gold (Au). The tip must under go a sharpening process much like a pencil. The probe tip starts off being a normal piece of wire made from one of the previously mentioned metals. The wire is placed in a bath of an etching solution to be etched. The etching solution contains NaOH or KOH. An electro chemical cell is then created using stainless steel plates as cathodes. Where the meniscus lies from the etching solution adhering to the wire a necking of the wire will take place. After a while in the etching solution the bottom portion of the wire will drop to the bottom of the beaker. The wire will neck down until it comes to a fine pin like structure. Depending on the type of applied voltage to the system (AC/DC) the tip can have different shapes. If the applied voltage is AC then the tip will have a conical shape to them and are more preferable for high-resolution imaging. If the applied voltage is DC then the tip will have a hyperboloid shape to it. If the portion of the wire in solution is to long then when the bottom portion of the tip falls to the bottom it could leave a rough end to the probe tip surface. It has been recommended that a 0.25mm diameter wire should only have 0.33mm submerged below the surface in order to maintain a smooth tip. Some of the other ways to manufacture the probe tips include: mechanical grinding, field emission/evaporation, ion milling and fracture. As can be seen in figure 13 the tip is etched.

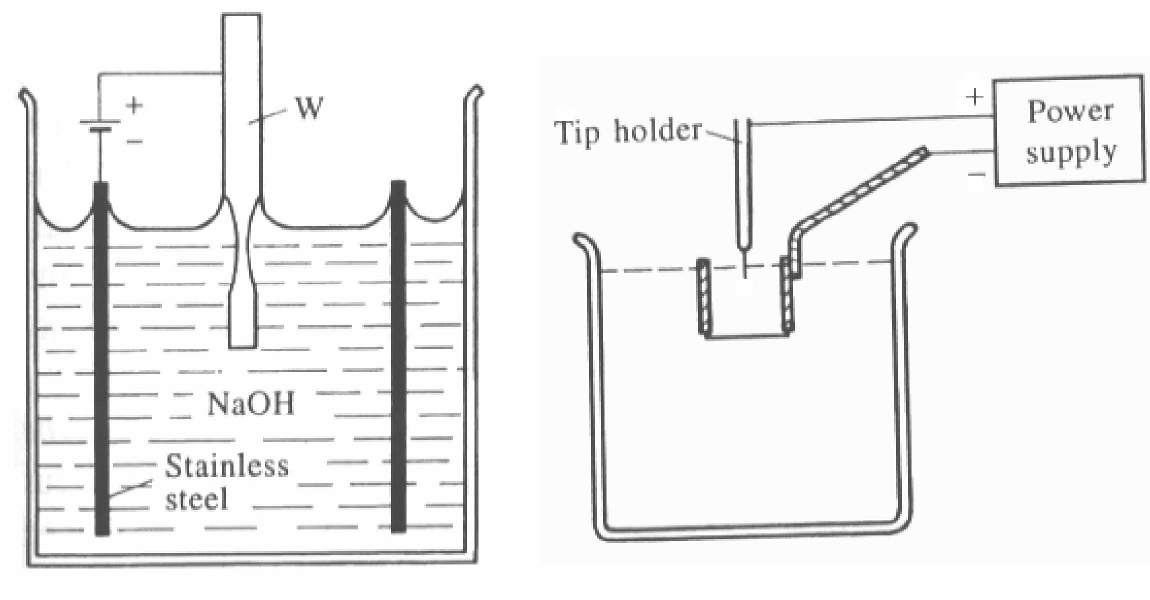


Figure 13. Probe Tip Construct by Etching (Bai, 1999)

Resolution of the material is greatly dependent on probe tip shape. As can be seen in figure 14, a 15° tip angle on a 50nm diameter wire is not as effective in determining the actual surface image. The more precise readings from the STM machine will require the smallest wire with the smallest tip angle possible.

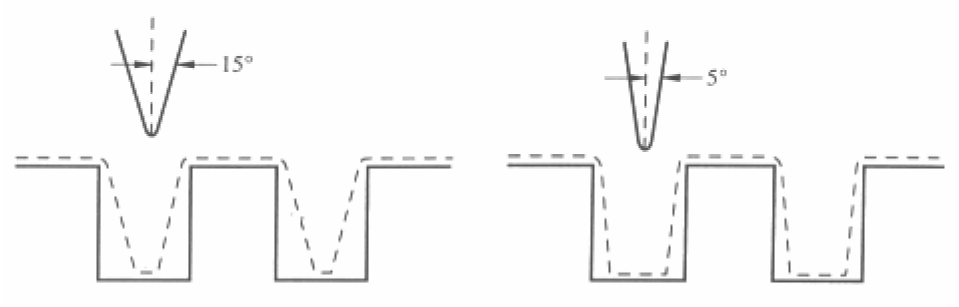


Figure14. Probe Tip Shape and Their Paths (Bai, 1999)

Typical resolution of an STM instrument is approximately 0.1nanometers laterally and 0.01 nanometers in the vertically.

**Atomic Force Microscopy**

Atomic Force Microscopy or AFM uses a cantilever probe tip to detect weak forces on a specimen. While the sample moves in the x-y direction the pointed end of the cantilevered probe can either make contact with the specimen surface or function in a non-contact mode. The scanning moves along the x-y direction and detects the extremely small repulsion forces from the probe and the surface of the specimen and moves up and down vertically following the shape of the surface. All of data can be collected by using lasers, piezo electric sensors or photoelectric sensors. The piezo electric sensors send a voltage to a transducer whenever a movement from the cantilever is made. The photoelectric sensor is able to measure movement based on changes in the incident angle made by changes cantilevers movement. The principle of the laser works in the same manner as the photoelectric sensor. Only in contact mode or in a state of strong repulsive forces can the highest resolution be achieved (Bai 1999). In Figure 15 we can see the three different sensors on the AFM Machine.

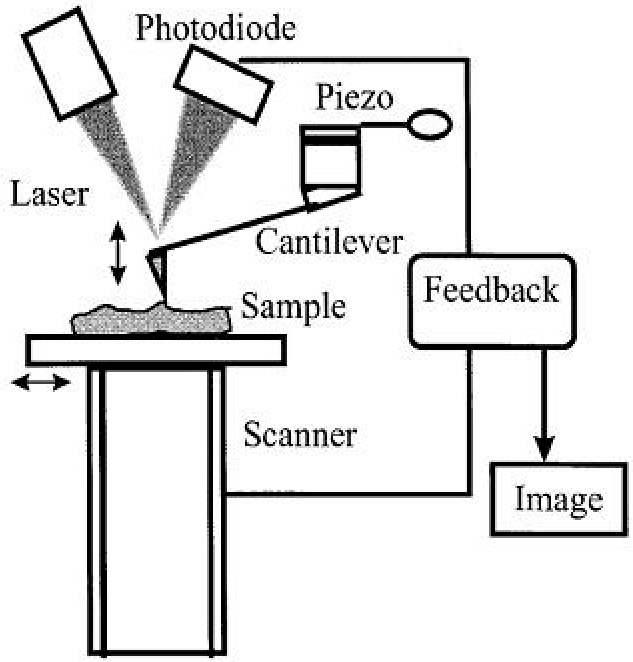


Figure 15. Working Principles of AFM( Ros-Yáñez, 2001)

In the figure 16 below we can see the light being transmitted down to the cantilever tip and how it is then transmitted up to the photodiode that will detect the incident angle. This form of detection will allow for very small changes in the incident angle.

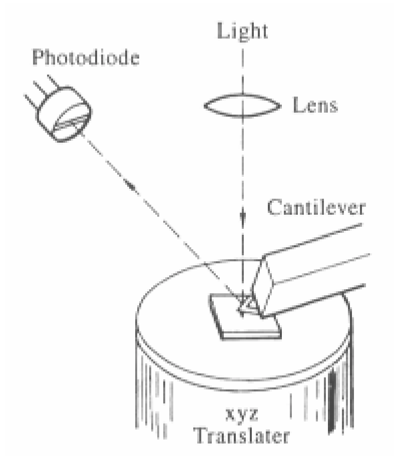


Figure 16. Diagram of Optical Beam Deflection (Bai, 1999)

## CONCLUSION

Surface roughness is an important factor when dealing with issues such as friction, lubrication, and wear. It also has a major impact on applications involving thermal or electrical resistance, fluid dynamics, noise and vibration control, dimensional tolerance, and abrasive processes, among others. In this review, the concept of roughness, as well as some of the parameters used to characterize it, were presented. Additionally, a brief survey of some of the roughness measurement techniques currently available was provided. Stylus profilers are the most common instruments used today for roughness measurement; however, more recent techniques such as STM and AFM have presented improved spatial resolution and are, therefore, suitable for capturing finer details (Poon and Bhushan, 1995). All techniques mentioned here have a common limitation, which is their inability to detect internal envelopes such as those caused by delamination (Thomas, 1998). This drawback may prevent researchers from obtaining valuable information regarding, for example, lubricant retention mechanisms.

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