Marvell Nanofabrication Laboratory University of California, Berkeley

Application Report

Chapter X.XX

Line and Surface Roughness Measurements with the Olympus LEXT OLS4000 Confocal Microscope

The OLS4000 software package has line and surface roughness measurement capabilities that allow rapid characterization of material surfaces. Resolution is specified to 10 nm in the z-height axis and is sample and material dependent. The following application note defines the may parameters used in surface nanometrology and explains basic roughness measurements using the Olympus OLS4000 microscope.

Line roughness measurements are taken along a line on the x-y plane of a sample that is specified in the OLS4000 software. The topography of the sample along this line is viewed as a cross-section and is referred to as the primary profile line. This profile is deconvoluted into wavelengths that are classified as roughness and waviness components (see Figure 4).

Typically, successive sample length measurements are taken over the period of an evaluation length (see Figure 1). ISO 4287, a well-recognized standard for roughness measurements, recommends the use of five sample length measurements within an evaluation length. Profile parameters from each of the five sample lengths are averaged to establish reported parameters such as Ra, Rz, etc. If more or less than five sample lengths are used, say six for example, the profile parameters are reported as Ra6, Rz6, etc.

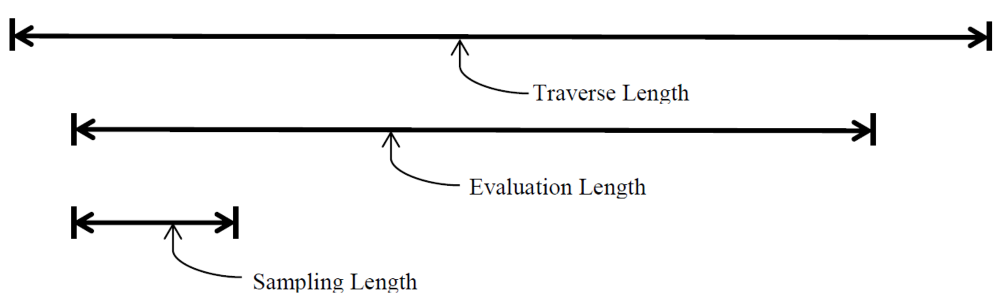


Figure 1. A relative comparison of sample, evaluation, and traverse lengths.

By default within the OLS4000 software package under the Line Roughness measurement feature (not to be confused with the Roughness measurement tab located on the bottom left side of the computer screen), the sample length is set equal to the evaluation length. The evaluation length is equal to the width of the field of view (defined by the magnification used) and can be adjusted by selecting Range Setting under the Profile Correction Section (see Figure 2).

Alternatively, traversing/scanning single line roughness measurements can be taken such that the sampling, evaluation, and traverse length is set to user defined values. This feature is located under the Evaluation Length window located in the Imaging (top left-most tab on the screen), Roughness (bottom left-most tab on the screen) tabs.

The sample length should be selected on the basis of gaining the best possible representation of the nature of the material's surface characteristics. A commonly practiced and well-accepted sample length is 800 um. When taken five times for averaging, this amounts to a total evaluation length of 4 mm. Keep this in mind when collecting profiles and measuring the nature of your material's surface.

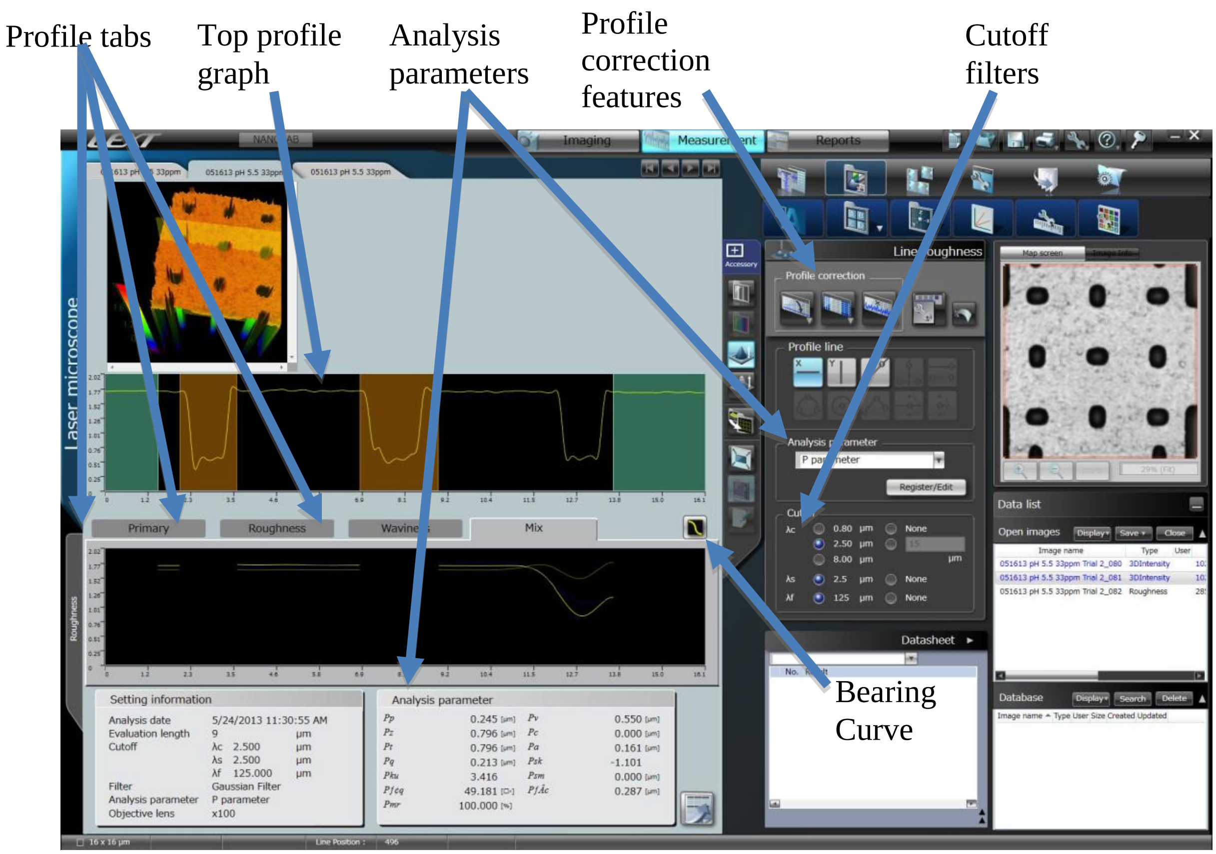


Figure 2. Line roughness measurement screen in the OLS4000 software.

PROFILE CORRECTION FEATURES:
These features manipulate and/or omit (ie. filter) portions of collected data and are often used to refine data so that it better represents the surface being measured. It is important to understand and consider what effect these corrections have on the measurements taken.

Profile Correction – Executes inclination correction (leveling) and curve correction (removing bow) algorithms. For additional profile corrections, various surface correction methods may be used under the Image Correction, Surface Correction menu. In general for samples with a rough surface, the Inclination (Auto) is a better choice than Inclination (3 points on an image).

Range Setting – Designates a range over which profile measurements are measured and calculated. This setting is used to define the location and distance of evaluation length. Once selected, the range bars are difficult to see; they are located at the far left and right edges of the top profile graph. Click and drag each edge and a bar used to set the range will become apparent.

Noise Exclusion – Defines regions that will be omitted from line profile calculations. Multiple exclusion regions can be defined by selecting the Set Exclusive Area option more than once. Exclusion areas can be reset by selecting the Noise Exclusion Off option.

CUTOFF:
Cutoff values are (high-, low-) pass filters that are used to define which wavelengths in the line profile are to be considered roughness or waviness. When combined they jointly act as a band-pass filter as shown in Figure 3.

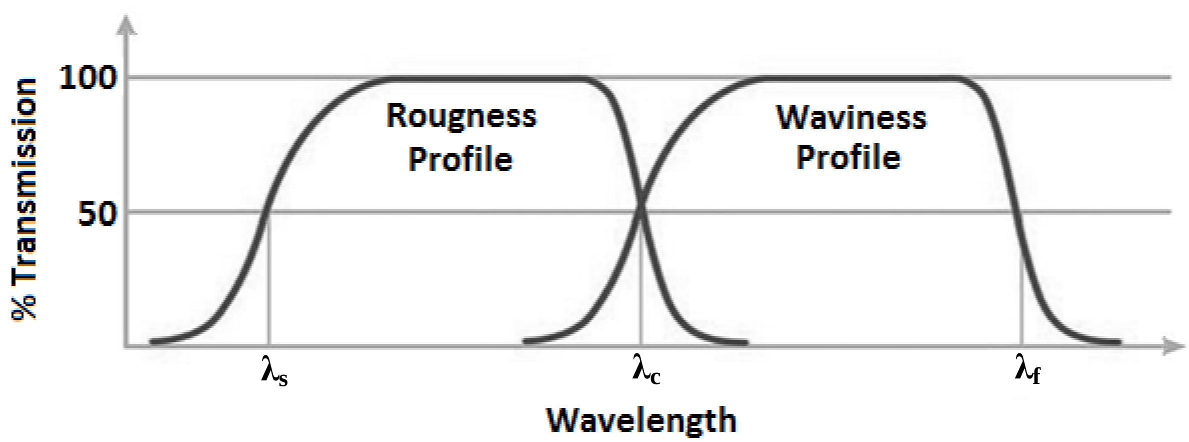


Figure 3. Visual representation of cutoff filters.

The OLS4000 software allows the following wavelength cutoffs:

- Roughness to waviness transition (aka, cutoff wavelength); λ_c = 0 µm (none), 8 µm, 25 µm,80 µm, or custom

- Short wavelength cutoff; λ_s = 0 um (none) or 2.5 µm
- Long wavelength cutoff; λ_f = 0 um (none) or 125 µm

Most modern equipment, including the Olympus microscope, uses a Gaussian probability function for filtering (see ISO 11562 for details). The use of a filter determines the shape of the tails see in Figure 3. Older instruments may use other filtering techniques such as 2RC. It is important to recognize any difference in filtering when comparing roughness measurements from multiple instruments.

PROFILE TABS:
By applying cutoff filters (see Cutoff section above), the evaluation length can be separated into primary, roughness, and waviness profiles (see Figure 4). These values have a large impact over each profile and special consideration should be made when choosing these values.

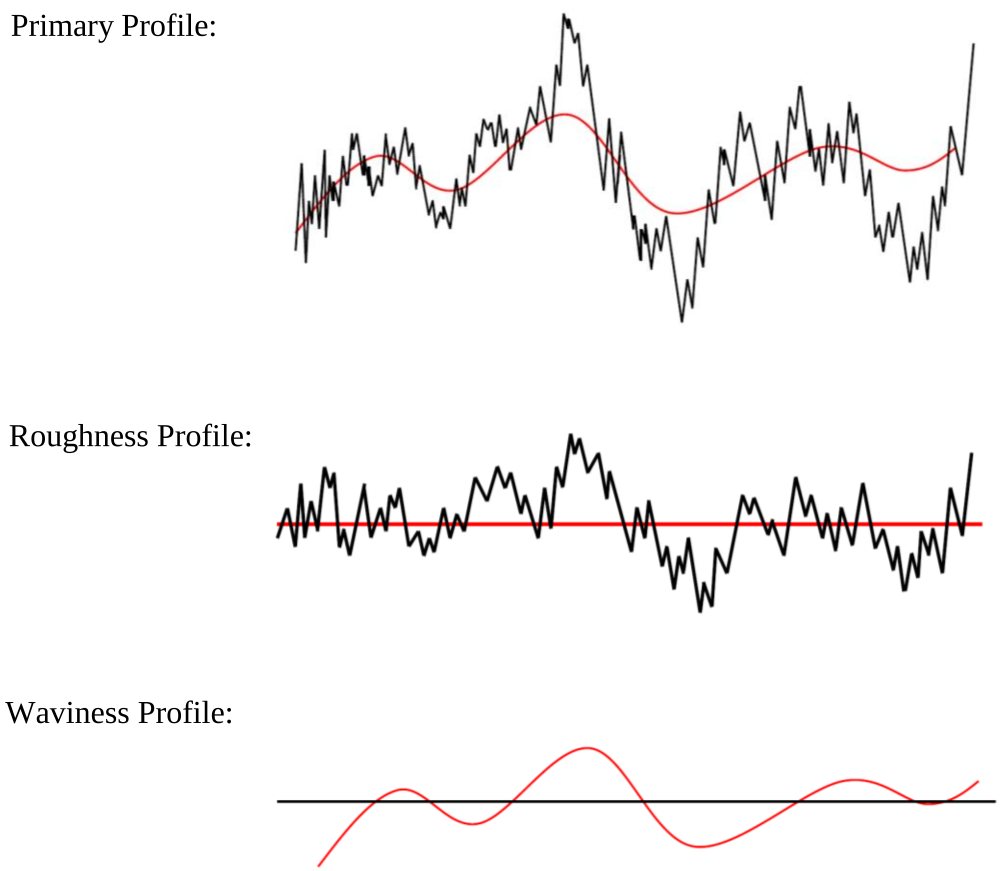


Figure 4. View of primary, roughness, and waviness profiles.

<u>Primary</u> – Profile view where parameters are measured over the sample length, which is equal to the evaluation length. The displayed profile is the total profile with the short wavelength, λ_s, applied and contains both roughness and waviness wavelengths. The primary profile is the basis for all primary parameters that start with P (P_p, P_v, P_z, etc.).

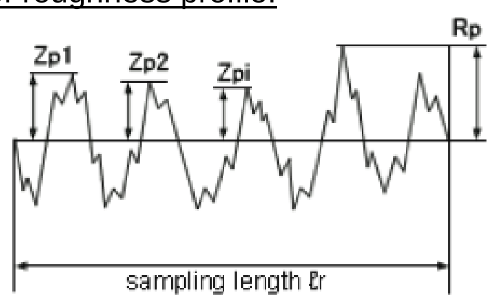
Roughness – Profile view resulting from the cutoff filter, λ_c, to the primary profile. Note the primary profile already has short wavelength, λ_s, applied. Thus, this is a profile with λ_c and λ_s applied. As λ_c increases, more features are included in the roughness profile and fewer are included in the waviness profile. The roughness profile is the basis for all roughness parameters that start with R (R_p, R_v, R_z, etc.).

Waviness – Profile view resulting from the application of the cutoff filters, λ_c and λ_f. As λ_c increases, fewer features are included in the waviness profile and more are included in the roughness profile. The waviness profile is the basis for all waviness parameters that start with W (W_p, W_v, W_z, etc.).

Mix – This profile view shows the primary, roughness, and waviness profile superimposed and is often used to observe the use of various cutoff filters. The thin yellow line and blue line are the roughness profile and waviness profile respectively.

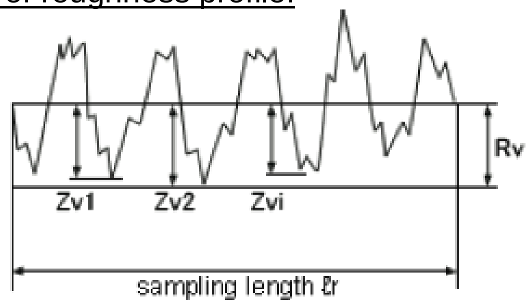
ANALYSIS PARAMETERS:
Parameters are calculated for each profile (ie. primary, roughness, and waviness) and are used to quantitatively characterize the surface of the material under investigation. The variable assigned to each parameter starts with a capital P, R, or W, and will correspond to the primary, roughness, and waviness profile respectively. **The most commonly used parameters are Xa, Xz, Xq, and Xsk**, where X is P, R, or W. Below is an explanation of the primary profile parameters found in the OLS4000 software. These explanations can also be applied to the roughness and waviness profiles, if the measurement described is taken from that specific profile.

R_p – Maximum peak height of roughness profile:



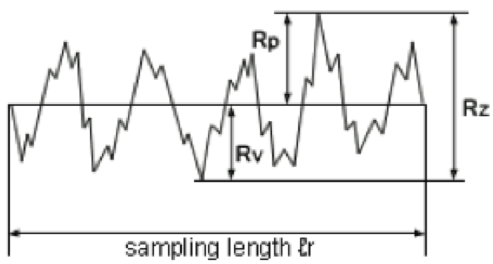
This is the largest peak height deviation from the mean line within a sample length.

R_v – Maximum valley depth of roughness profile:



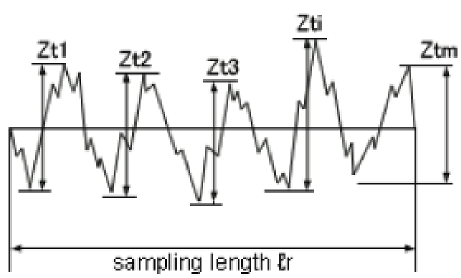
This is the largest valley depth deviation from the mean line within a sample length.

R_z – Maximum primary height of roughness profile:



This is the sum of the maximum peak height, $R_{p,}$ and maximum valley depth, R_v within a *sample* length.

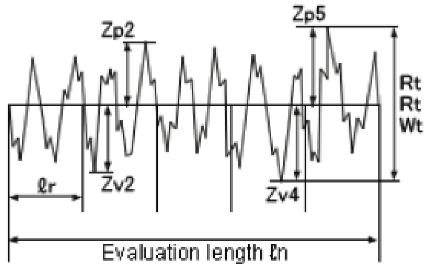
R_c – Mean height of roughness profile features:



$$P_c = \frac{1}{m}\sum_{i=1}^{m} z_{ti}$$

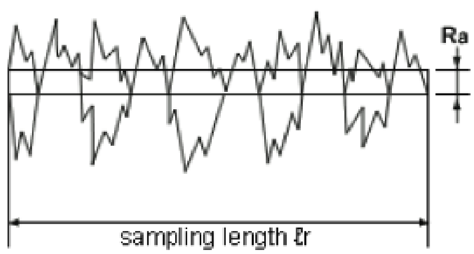
Not commonly used or widely accepted.

R_t – Maximum primary height of roughness profile:



Sum of the maximum peak height, $R_{p,}$ and maximum valley depth, R_v, in an *evaluation* length. This parameter has no averaging effect because it is taken over the evaluation length, as opposed to an average over five sample lengths such as in R_z. As such, scratches, contamination, and other defects strongly influence this parameter.

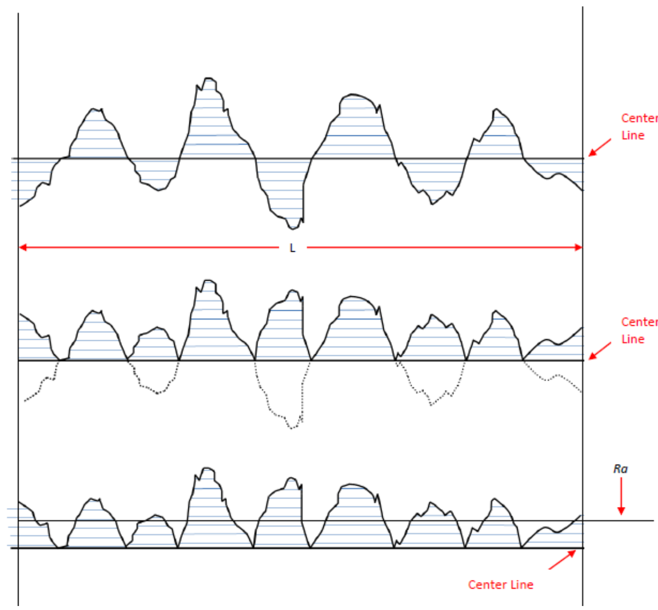
R_a – Arithmetic mean deviation of the roughness profile:



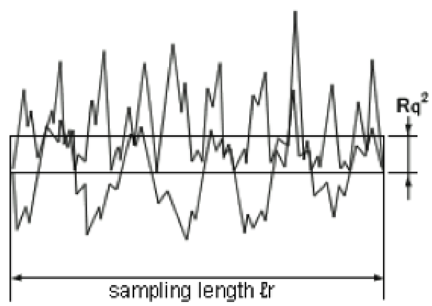
This is the average of the absolute z(x) values, over the sample length, *l*.

$$P_a = \frac{1}{l}\int_0^l |z(x)|dx \approx \frac{1}{n}\sum_{i=1}^{n}|z_i|$$

This is the average roughness over the sample length. A single non-typical feature will only have a slight effect of this parameter. To ensure the R_a is representative of the surface under investigation, it is recommended to average the R_a of several consecutive sampling lengths. These measurements should be taken perpendicular to the lay. It should be noted that this parameter does not provide useful information on the shape of surface texture.



R_q – Root mean square (RMS) deviation of the roughness profile:



This is the root mean square of z(x) calculated over the sample length, *l*.

$$P_q = \sqrt{\frac{1}{l}\int_0^l (z(x))^2\,dx} \approx \sqrt{\frac{1}{n}\sum_{i=1}^{n}(z_i)^2}$$

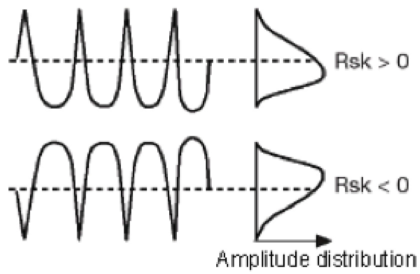
This parameter is often used to describe the optical quality of a surface. It is directly related to the total spectral content of a surface because of the averaging of the squared magnitude components.

R_{sk} – Skewness of the roughness profile:

This is a measurement of the symmetry of surface deviations from the mean reference line. It is found by taking the ratio of cubed mean height values to the cubed RMS deviation, R_q within the sample length, *l*.

$$P_{sk} = \frac{1}{P_q^3}\left[\frac{1}{l}\int_0^l (z(x))^3\,dx\right] \approx \frac{1}{P_q^3}\left[\frac{1}{n}\sum_{i=1}^{n} z_i^{\ 3}\right]$$

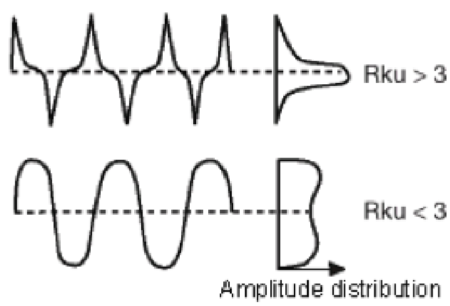
A surface with a random amplitude distribution about the mean line has a R_{sk} equal to zero. A positive R_{sk} means that the surface has high peaks protruding above the mean line and the bulk of the material is below the mean line. Conversely, a negative R_{sk} is a result of the surface having large valleys protruding below the mean line and the bulk of the material is above the mean line.



When looking at the tribology of bearing surfaces, a negative R_{sk} is usually desirable because the surface has few protruding peaks that can wear quickly and deep valleys to retain lubricants. R_{sk} commonly correlates to the material loading capabilities and porosity of a material.

<u>R_{ku} – Kurtosis of the roughness profile:</u>

This is the sharpness of the surface height distribution and characterizes the spread of the height distribution across a sample length.



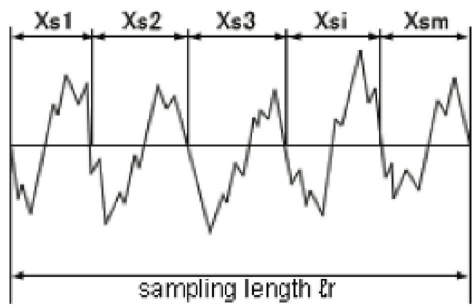
It is found by taking the fourth power of the mean height values to the fourth power of the RMS deviation, R_q, over the sample length, *l*.

$$P_{ku} = \frac{1}{P_q^4}\left[\frac{1}{l}\int_0^l (z(x))^4\,dx\right] \approx \frac{1}{P_q^4}\left[\frac{1}{n}\sum_{i=1}^{n} z_i^4\right]$$

If R_{ku} = 3, there is a Gaussian distribution of height. If R_{ku} > 3, the spread of height distribution is narrow and the surface has many spikes. If R_{ku} < 3, there is a broad spread in the height distribution and the surface is bumpy. It is important to note that this parameter does not distinguish between peak and valley.

R_{sm} – Mean width of the roughness profile elements:

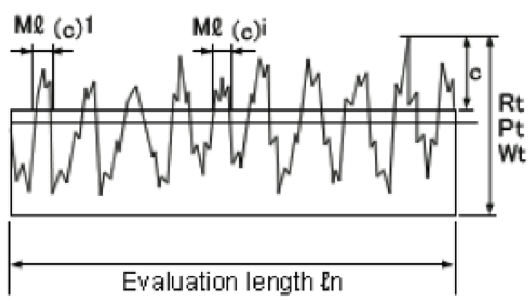
This is the average distance along the mean height line that contains a profile element containing both a profile peak and according valley.



R_{mr} – Load length profile:

This is the ratio of the load length, Ml(c), of profile element at cut level, c, to evaluation length, *l*.

$$P_{mr} = \frac{Ml(c)}{l}$$



R_{zjis} – Ten point mean roughness:

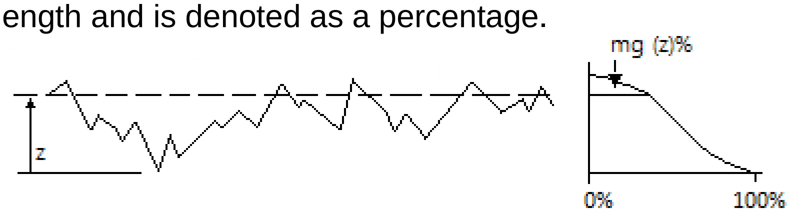
This is the average of the sum of the five highest profile peaks, z_{pi}, and the five deepest profile valleys, z_{vi}, over the sample length, *l*.

$$P_{zjis} = \frac{1}{5}\sum_{i=1}^{5}\left(z_{pi} + z_{vi}\right)$$

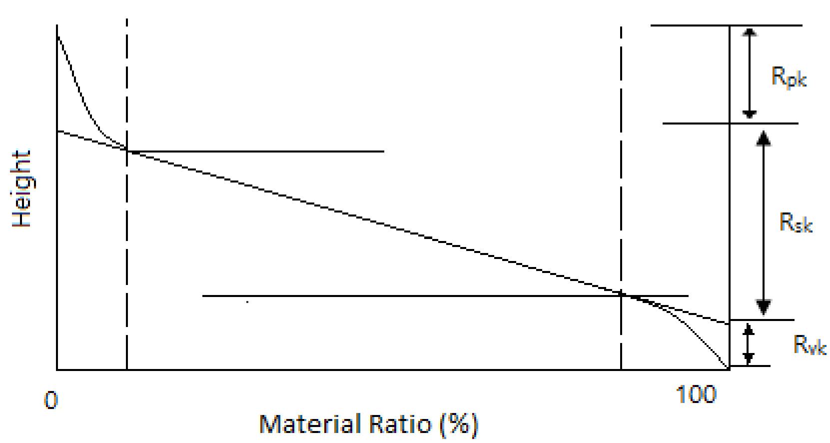
Bearing Curve / ADC:
These parameters can be found by selecting an icon that is located to the right of the profile tabs (see Figure 2).

Height Difference – The percentage difference in height the level line (a line parallel to the mean line) is to the highest point in the profile. If the level line is at the highest point of the profile, the height difference is 0%. If the level line is at the lowest point of the profile, the height difference is 100%.

Material Ratio – The ratio of the sum of the section lengths taken at a given level line height to the evaluation length and is denoted as a percentage.



Material Ratio Curve – This is the curve on the left hand side under the Bearing Curve / ADC icon. This is also known as the Abbot-Firestone or bearing curve and shows the material ratio as a function of height difference. This can be thought of as the percentage of the profile that is above the level line. It is useful for distinguishing different shapes within a profile. If the profile is fairly flat, the material ratio curve will be fairly flat. If there are large peaks or valleys in the sample, the material ratio curve will be relatively steeper.



Amplitude Distribution Curve – This is the curve on the right hand side under the Bearing Curve / ADC icon. This is a probability function that gives the probability the profile has a given height at a given position. This curve can be thought of as a histogram showing how much of the profile lies at a particular height.

Related Reading

1. OLS4000 Help Documents - The Definition of Analysis Items in Roughness Analysis (Line Roughness Analysis), Olympus, pg. 100, 2012.
2. Handbook of Surface and Nanometrology, David J. Whitehouse, CRC Press, Boca Raton, FL, pg. 5, 2011.
3. Fundamental Principles of Engineering Nanometrology, Richard K. Leach, Elsevier Inc., Ch 6 and 8, 2010.

J. Clarkson – June 2013