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Understanding Surface Quality: Beyond Average Roughness (Ra)

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Understanding Surface Quality: Beyond Average Roughness (R_a)

Abstract

Design of machine parts routinely focus on the dimensional and form tolerances. In applications where surface quality is critical and requires a characterizing indicator, surface roughness parameters, R_a (roughness average) is predominantly used. Traditionally, surface texture has been used more as an index of the variation in the process due to tool wear, machine tool vibration, damaged machine elements, etc., than as a measure of the performance of the component. There are many reasons that contribute to this tendency: average roughness remains so easy to calculate, it is well understood, and vast amount of published literature explains it, and historical part data is based upon it. It has been seen that Ra, typically, proves too general to describe surface's true functional nature. Additionally, the push for complex geometry, coupled with the emerging technological advances in establishing new limits in manufacturing tolerances and better understanding of the tribological phenomena, implies the need for surface characterization to correlate surface quality with desirable function of the surface. In turn, the surface quality over the entire area, not just the 2D R_a parameter, dictates the performance and reliability of the part.

Both ISO and ASME current standards on surface texture have a range of 3D surface quality parameters. This is further aided by the availability of modern equipment to accurately measure them. Despite these advances, design and quality professionals continue to specify surface finish based solely on the value of R_a. The same outlook trails in graduate and undergraduate education and their textbooks. This article explores how these multitudes of 2D and 3D surface quality parameters are to be understood in the design and development of high performance surfaces, and the strong need for them to be incorporated into graduate undergraduate engineering curriculum, and be taught as an improved toolkit to the aspiring engineers, process engineers and quality control professionals. Included case studies can be used to captivate the attention of the students (target audience would include industry professionals as well) and route their inquisitiveness into why they need to think beyond Ra in this era of advanced manufacturing.

Introduction

Choice of tool; feed and speed of the tool; machine geometry; and environmental conditions in machining processes result in the irregularity of machined surface. This irregularity consists of high and low spots machined into a surface by the tool bit. These peaks and valleys can be measured and used to define the condition and sometimes the performance of the surface [1]. In today's world, there are more than 100 ways to measure a surface and analyze the results, but the most common measurement of the mark made by the tool, or the surface texture, is the roughness measurement.

Numerous articles [2-11] have tried to address the dependence of the condition of surface and its performance on the machining process parameters. However, they have thus far, focused on only one parameter, namely, Ra. The average roughness, Ra is also known as AA (arithmetic average) or CLA (center line average). Traditionally, this has been the only roughness parameter to appear on the drawings, and parts have been only been inspected for this parameter. Critical concepts in wear, friction and lubrication, fatigue, etc. have been discussed and analyzed based on Ra alone. While Ra remains useful as a general guideline of surface texture, it typically proves too general to describe the surface's functional nature. A surface with sharp spikes, deep pits, or general isotropy may all yield the same average roughness value, Ra makes no distinction between peaks and valleys, nor does it provide information about spatial structure [12].

In order to understand what other parameters exist to effectively and efficiently characterize surface conditions, we need to understand them in their mathematical context as well as in the context of their design/application requirements. In this paper, we will discuss the limitations of 2D parameters and, more importantly, how 3D parameters can be employed to provide greater insight into surface finish and performance. Additionally, few case studies have been presented to corroborate the same.

Mathematical Understanding of Surface

Quantifying surface irregularities means assessing them by categorizing them by height, depth, and interval. They are then analyzed by a predetermined method and calculated per industrial quantities standards. The form and size of surface irregularities and the way the finished product will be used determine if the surface roughness acts in a favorable or an unfavorable way. Painted surfaces should be easy for paint to stick to, while drive surfaces should rotate easily and resist wear. It is important to manage surface roughness so that it is suitable for the component in terms of quality and performance. There are close to 100 different parameters for describing surface finishes or conditions. Selecting the most suitable can be difficult, and usually it takes at least two to reasonably describe a surface. A typical engineering surface consists of a range of spatial frequencies. The high frequency or short wavelength components are referred to as roughness, the medium frequencies as waviness and low frequency components as form. Figure 1 illustrates this [13].

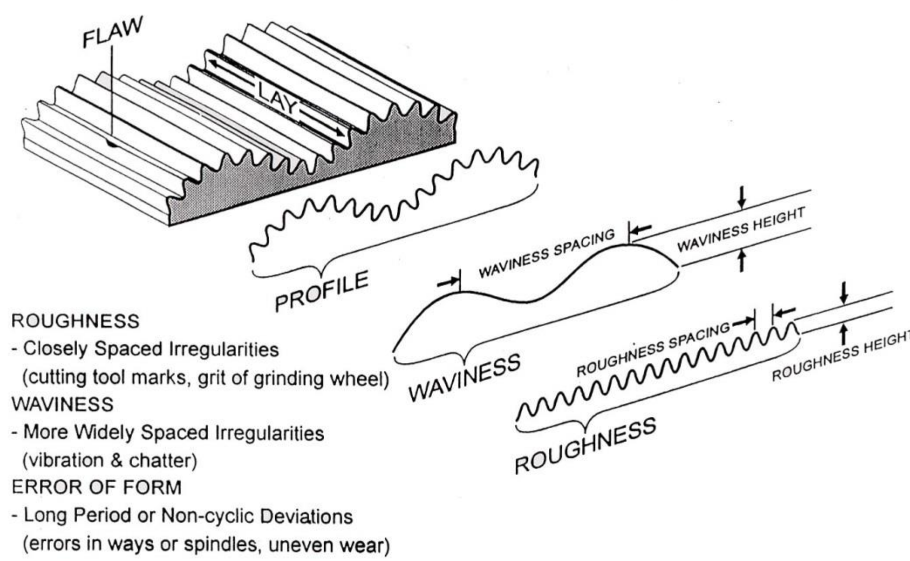


Figure 1. Form Error, Waviness and Roughness [13].

Historically, it has been accepted that different aspects of the manufacturing process generate the different wavelength regimes and these affect the function of the part differently [13,14]. As shown in figure 2, by separating surface profile into various bands, we can map the frequency spectrum of each band to the manufacturing process that generated it. Thus, filtering of surface profiles serves as a useful tool for process control and diagnostics.

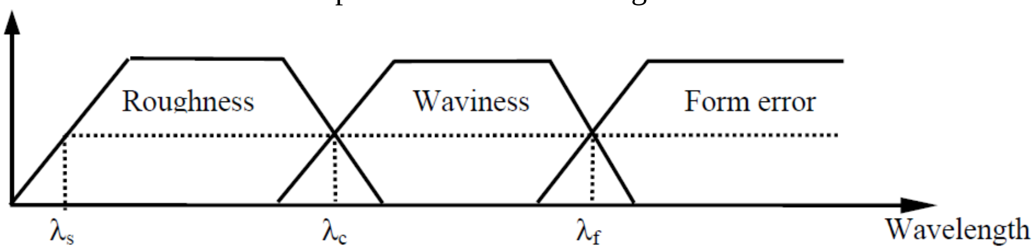


Figure 2. Separation of surface into frequency bands [14].

While engineers commonly trace manufacturing process variations based on surface profile data, mapping functional performance of a component based on surface profile information has been a challenge. The different wavelength regimes play a key role in critical parts. Thus, separation of signal into various bandwidths has to be viewed from a functional standpoint as well. Digital filtering is a common practice to separate a signal into various regimes. Analog RC filters have been replaced by the now common Gaussian filters. Form errors (like flatness, straightness, roundness and cylindricity) include the crudest (highest wavelength) irregularities on the surface. They are commonly measured using layout gages and Coordinate Measuring Machines (CMM) based on Geometric Dimensioning and Tolerancing (GD&T) standards. These irregularities can be quantified based on deviations measured from a nominal surface. Roughness includes the finest (shortest wavelength) irregularities of a surface. Roughness generally results from a particular production process or material condition. Waviness includes the more widely spaced (longer wavelength) deviations of a surface from its nominal shape. Waviness errors are intermediate in wavelength between roughness and form error. Lay refers to the predominant direction of the surface texture.

Surface Roughness Measurement Tools (Contact-Type)

In most of the contact-based measurement tools, traces are done 90° to "lay" with a conical diamond stylus. The radius of the stylus tip is usually in the range of 2-10 µm. In a skidded measurement tool (as shown in figure 3), the skid and the diamond stylus are independent, and are in contact with the surface. The skid and diamond follow the surface during measurement. The surface deviations are measured by the change in the diamond position relative to the plane of the skid. Skidded instruments measure only roughness. Waviness is filtered out by the skid following the surface. Most portable instruments are skidded. In skidless instruments (as shown in figure 4), the diamond stylus alone follows the surface during measurement. Deviations are measured by the change in the diamond position relative to the drive datum guide. Skidless instruments measure roughness, waviness and profile.

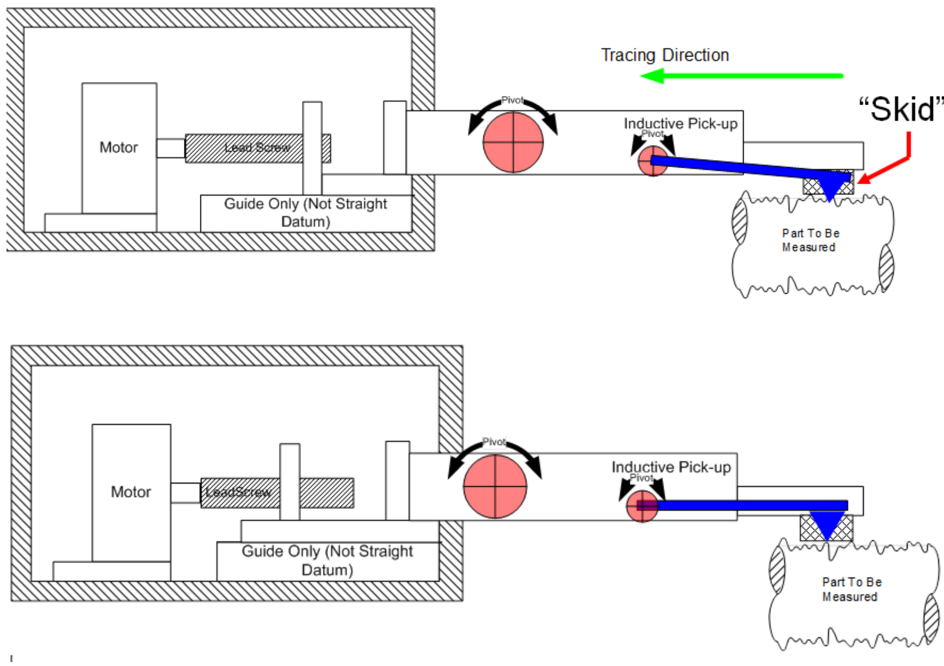


Figure 3. Skidded Measurement Tool.

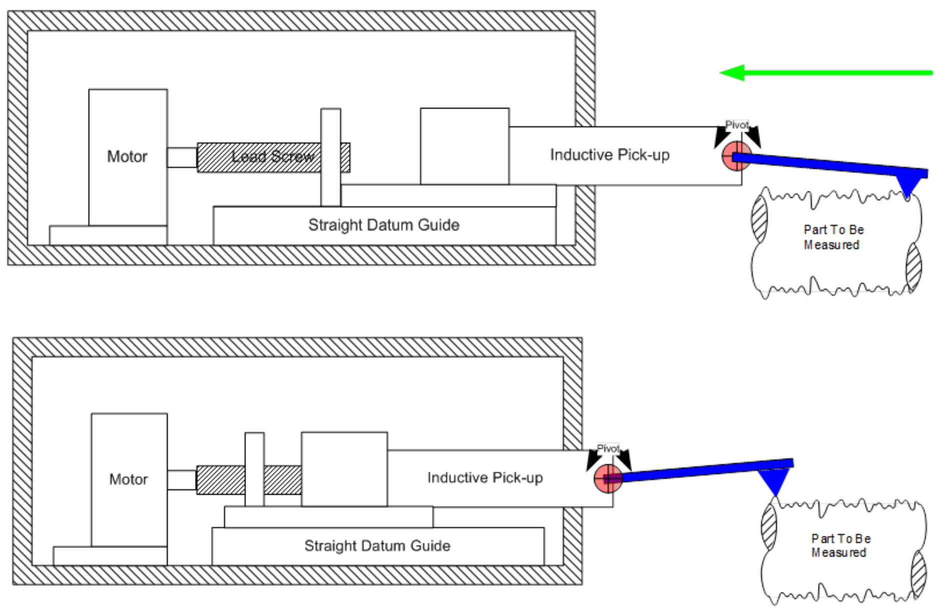


Figure 4. Skidless Measurement Tool.

Filters in Surface Roughness

To separate wavelengths, a filter is applied to the profile data. Digital filters commonly used are RC type (simulated old analog electrical "resistor capacitor") and Gaussian type. The user selects the "cutoff" setting used by the filter to separate profile into roughness and waviness. Filtered data is centered around a mean line. This is shown in figure 5.

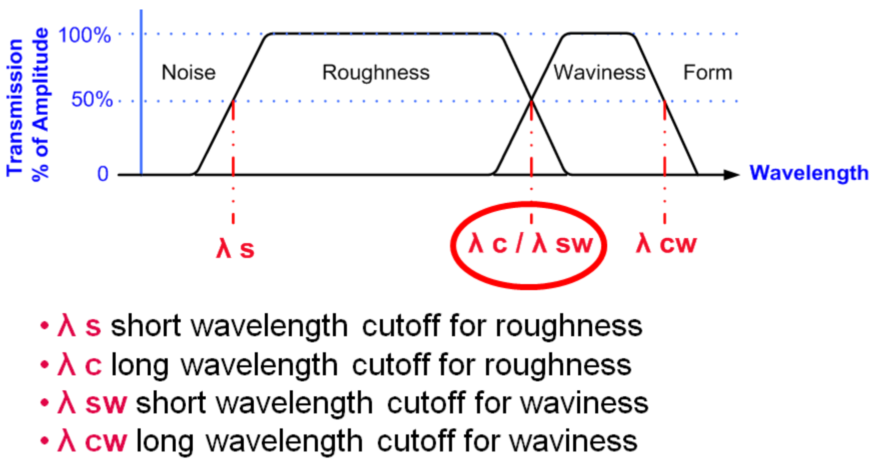


Figure 5. Filter Transmission and Cutoff.

The cutoff value is the longest nominal wavelength to be included in roughness. Wavelengths longer than the roughness cutoff are included in waviness. Cutoff functions in a manner similar to a sieve (shown in figure 6). The cutoff selected must be short enough to exclude long wavelengths (waviness). Figure 7 demonstrates the effects of cutoff filter selection. For the same profile data, selection of λc = 0.08 mm results in Ra = 0.560 µm and waviness Wa = 0.827 µm., while selection of λc = 0.8 mm results in Ra = 1.149 µm and waviness Wa = 0.229 µm.. Hence it demonstrates that higher wavelengths were used in the second situation that raised Ra while reducing Wa.

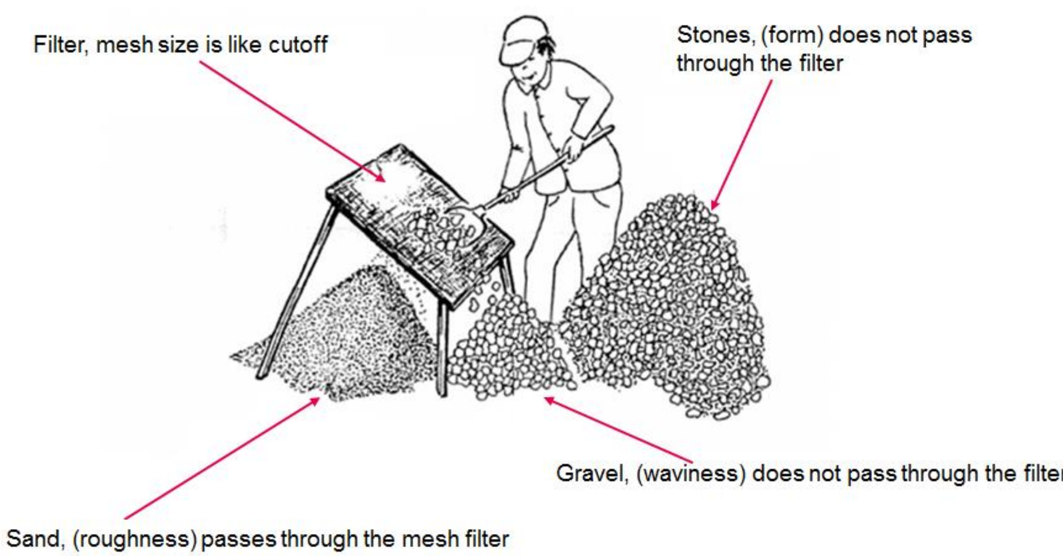


Figure 6. The role of roughness “Cutoff” (λc) filter.

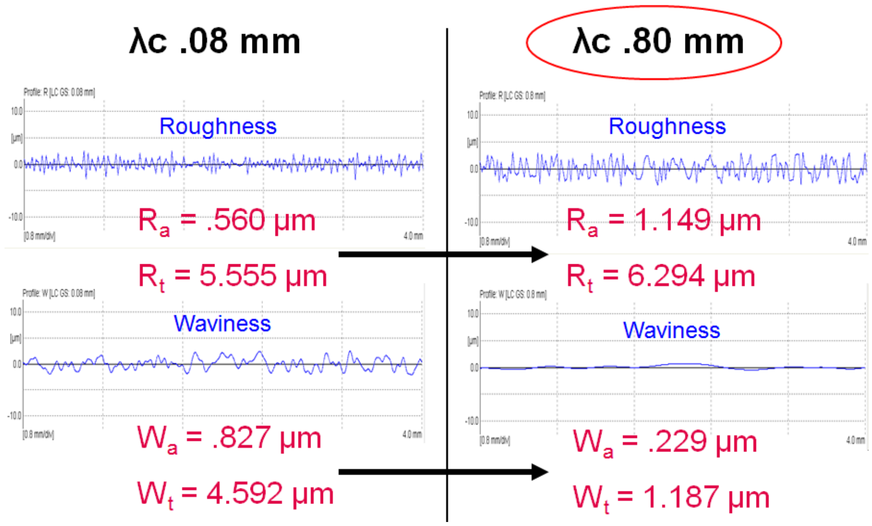


Figure 7. Effect of roughness "Cutoff" (λc) filter setting.

Mathematical Modeling of Profiling Methods

Although there are about 100 parameters in existence, for the brevity of this paper, only a few have been explained here. For mathematical definition of the rest, reader can look up reference [14]. Key quantities that distinguish one profile from another are their height deviations from nominal profile and the distances between comparable deviations. Various mathematical combinations of surface profile heights and spacings have been devised to compare certain features of profiles numerically.

Height (z) Parameters

(1) **Roughness Average (Ra)**

Ra is the most commonly specified parameter in USA. Confusion exists between Ra and RMS values. Ra is developed from RMS, but they are not same. As shown in figures 8 and 9, Roughness average is the arithmetic average of the absolute values of the roughness profile ordinates. Analytically, Ra is given by the following equation, where Z(x) is the profile height function used to represent the point-by-point deviations between the measured profile and reference mean line. For digital instruments, Z(x) is approximated by a set of digitized values (Z_i) recorded using the sampling interval (d_0).

$$Ra = \left(\frac{1}{L}\right) \int_0^L |Z(x)| dx \tag{1}$$

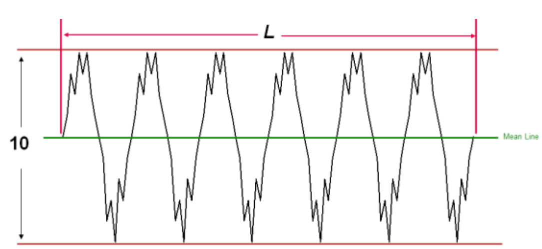


Figure 8. Filtered roughness profile with mean line, peak to valley is 10

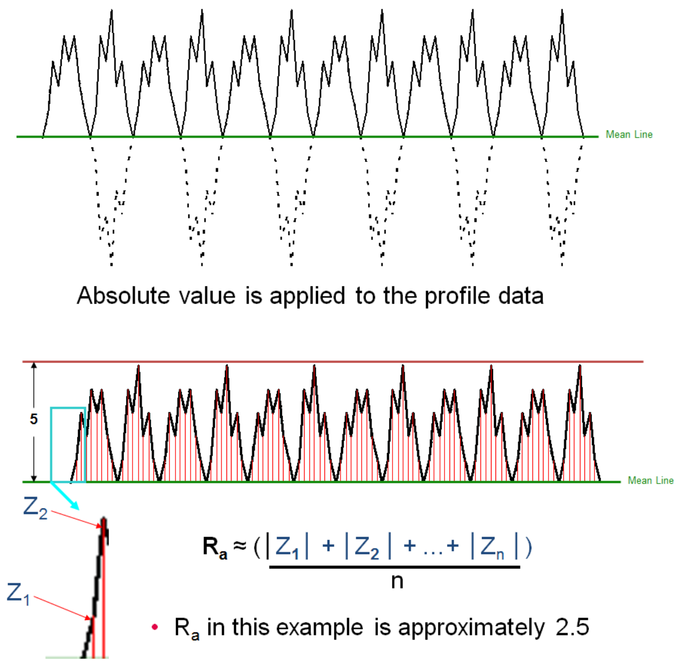


Figure 9. Steps for the calculation of Ra.

(2) **Root Mean Square (rms) Roughness Average (Rq)**

Rq is the root mean square average of the profile height deviations taken within the evaluation length and measured from the mean line. Analytically, it is given by the following equation,

$$Rq = \left[\left(\frac{1}{L}\right)\int_0^L (Z(x))^2 dx\right]^{1/2} \quad (2)$$

The digitized approximation is as follows,

$$Rq = \left[(Z_1^2 + Z_2^2 + Z_3^2 + \cdots \ldots \ldots Z_N^2)/N\right]^{1/2} \quad (3)$$

(3) **Maximum Profile Peak Height (Rp)**

It is the distance between the highest point of the profile and the mean line within the evaluation length. R_{pi} is the distance between the highest point of the profile and the mean line within a sampling length segment labeled *i* (figure 10).

(4) **Average Maximum Profile Peak Height (Rpm)**

It is the average of the successive values of *Rpi* calculated over the evaluation length.

(5) **Maximum Profile Valley Depth (Rv)**

It is the distance between the lowest point of the profile and the mean line within the evaluation length (figure 10).

(6) **Maximum Height of the Profile (Rt)**

It is the vertical distance between the highest and lowest points of the profile within the evaluation length (figure 10).

$$Rt = Rp + Rv \quad (4)$$

***(7)* Average Maximum Height of the Profile (Rz)**

It is the average of the successive values of *Rti* calculated over the evaluation length (figure 10). Rz is the second most commonly specified parameter. Confusion exists since it can be calculated five different ways. So the user must ensure to understand which standard governs. Do not attempt to estimate Rz using a conversion factor. Ra, is not greatly influenced by spikes in the profile. However, Rz, is greatly influenced by those spikes.

***(8)* Maximum Roughness Depth (Rmax)**

It is the largest of the successive values of *Rti* calculated over the evaluation length (figure 11).

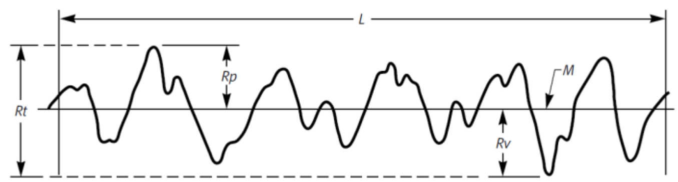


Figure 10. Rt, Rp and Rv Parameters.

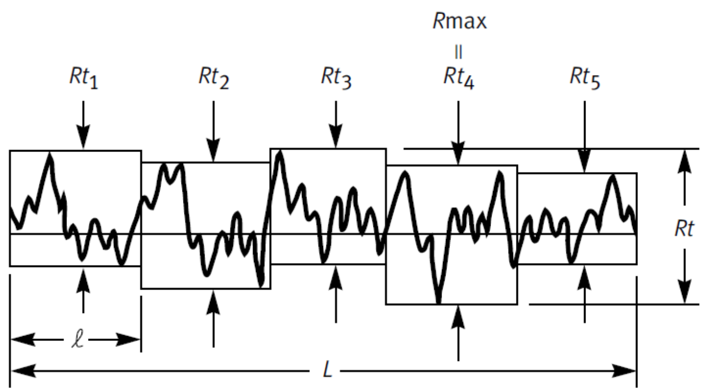


Figure 11. Rt and Rmax Parameters.

<u>**Waviness Height Parameters**</u>

***(1)* Waviness Height, Wt**

It is the peak-to-valley height of the modified profile from which roughness and part form have been removed by filtering, smoothing, or other means. The measurement is to be taken normal to the nominal profile within the limits of the waviness evaluation length (figure 12).

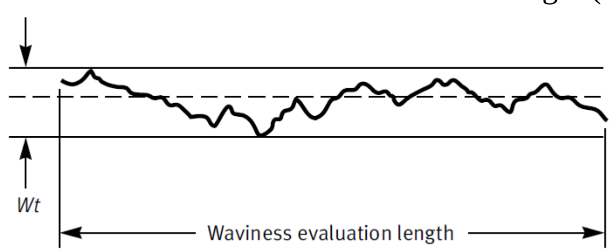


Figure 12. Waviness Height, Wt

<u>Spacing Parameters</u>
It is a distance that characterizes the lateral spacings between the individual profile asperities.

(1) **Mean Spacing of Profile Irregularities (RSm)**

It is the mean value of the spacing between profile irregularities within the evaluation length (figure 13).

$$RSm = \left(1/n\right) \sum_{i=1}^{n} Sm_i \tag{5}$$

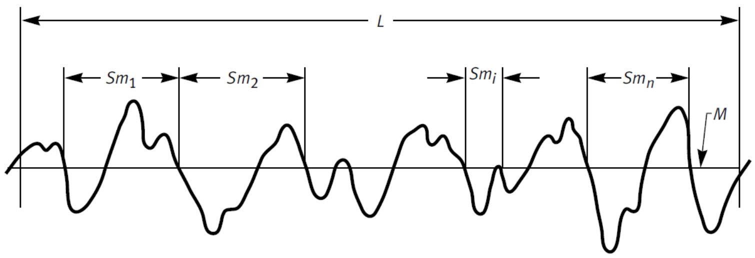


Figure 13. The Mean Spacing of Profile Irregularities, RSm.

<u>Shape Parameters and Functions</u>

(1) **Amplitude Density Function, ADF(z) or p(z)**

It is the probability density of surface heights. The amplitude density function is normally calculated as a histogram of the digitized points on the profile over the evaluation length (figure 14).

(2) **Profile Bearing Length**

It is the sum of the section lengths obtained by cutting the profile peaks by a line parallel to the mean line within the evaluation length at a specified level *p*. The level *p* may be specified in several ways including the following:

(a) As a depth from the highest peak (with an optional offset)
(b) As a height from the mean line
(c) As a percentage of the *Rt* value relative to the highest peak (figure 15).

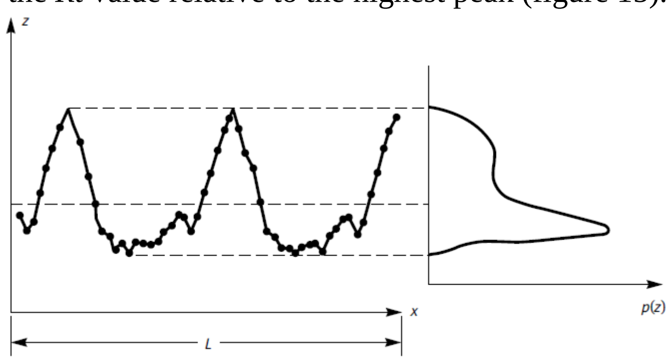


Figure 14. Amplitude Density Function – ADF(z) or p(z)

(3) **Profile Bearing Length Rati, tp**

It is the ratio of the profile bearing length to the evaluation length at a specified level *p*. The quantity *tp* should be expressed in percent.

$$tp = \frac{b1+b2+\cdots+bn}{L} \times 100\% \tag{6}$$

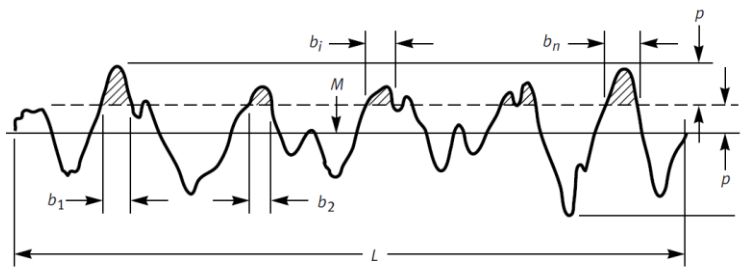


Figure 15. The profile Bearing Length

(4) **Bearing Area Curve, BAC**

It is (also called the Abbott-Firestone curve) related to the cumulative distribution of the ADF. It shows how the profile bearing length ratio varies with level (figure 16).

(5) **Skewness, Rsk**

It is a measure of the asymmetry of the profile about the mean line calculated over the evaluation length (figure 17). In analytical and digitized form,

$$Rsk = \frac{1}{{R_q}^3}\frac{1}{L}\int_0^L [z(x)]^3 dx \tag{7}$$

$$Rsk = \frac{1}{R_q^3}\frac{1}{N}\sum_{j=1}^{N} Z_j^3 \tag{8}$$

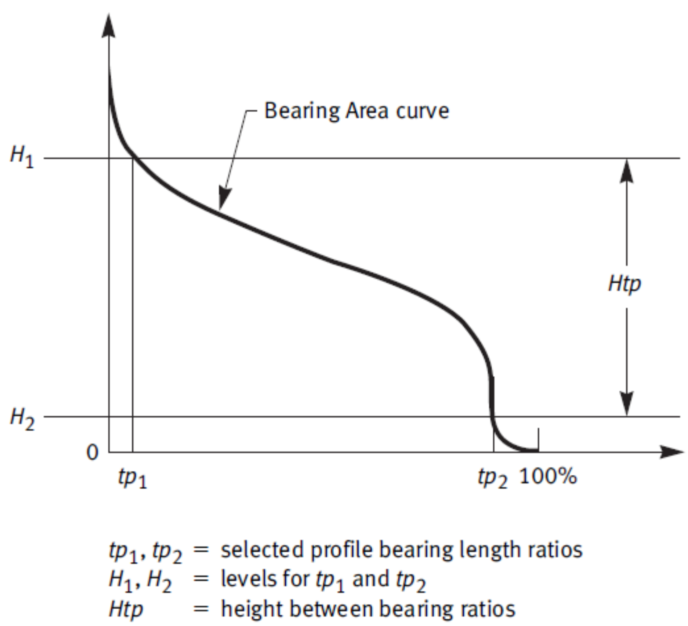


Figure 16. The Bearing Area Curve and Related Parameters.

(6) **kurtosis, Rku**

It is a measure of the peakedness of the profile about the mean line calculated over the evaluation length (figure 18). In analytical and digitized form,

$$Rku = \frac{1}{{R_q}^4}\frac{1}{L}\int_0^{L3}[z(x)]^4 dx \quad (9)$$

$$Rku = \frac{1}{R_q^4}\frac{1}{N}\sum_{j=1}^{N} Z_j^4 \quad (10)$$

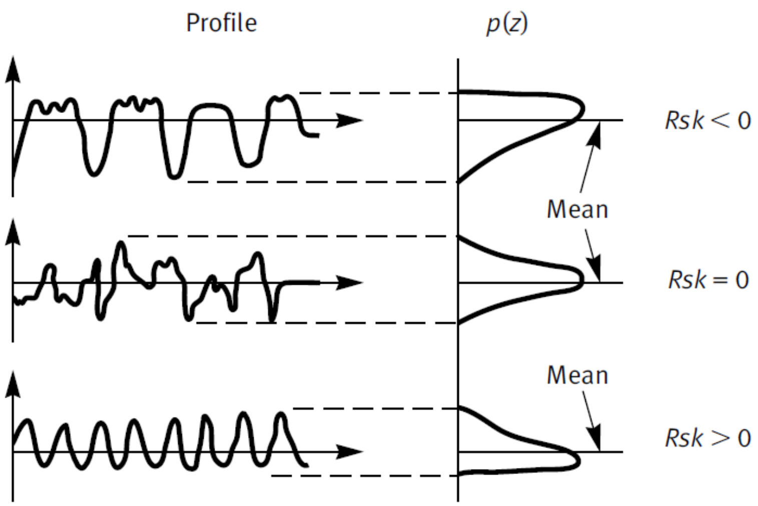


Figure 17. Three Surface profiles with Different Skewness.

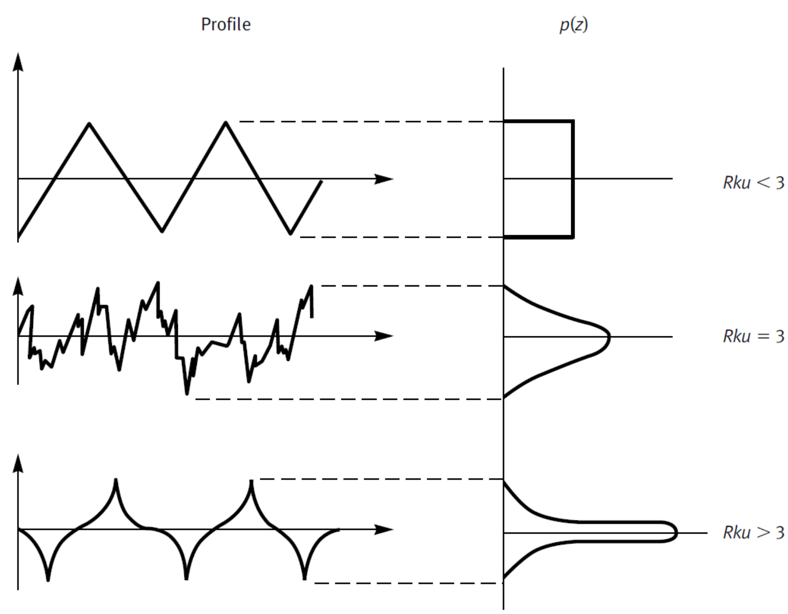
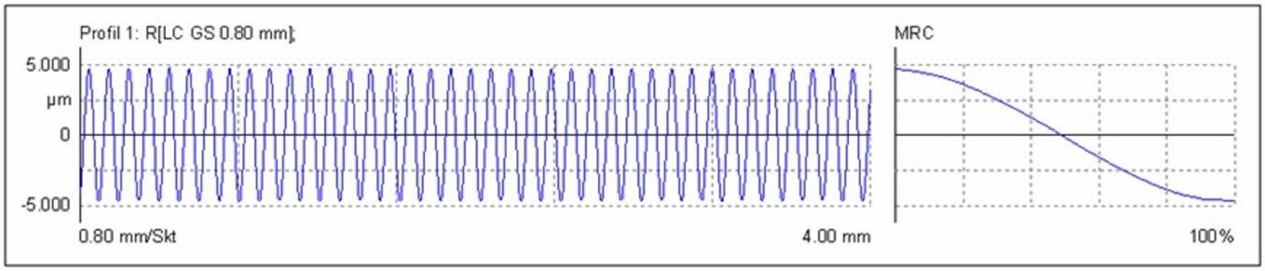


Figure 18. Three Surface profiles with Different Kurtosis.

Hybrid Parameters

(1) Linear Material ratio Curve Height Parameters

These are related to the profile bearing length in the linear material ratio curve, also known as the bearing area curve. Parameters Rpk, Rk, Rvk, Mr1, and Mr2 derived from the linear material ratio curve. As shown in figure 19, Material Ratio expresses the theoretical contact ratio at a given cutting depth. In this sine wave example, 5 µm depth yields 50% contact ratio.



Roughness parameters - profile 1: R[LC GS 0.80 mm];						
Ra	2.9829	µm				
R Mr (-1.00, 0.0)	19.61	%				
R Mr (-5.00, 0.0)	51.29	%				
R Mr (-10.00, 0.0)	100.00	%				

Figure 19. Example to calculate Material Ratio.

Figure 20 shows more profiles with their Bearing area Curves. Further, figure 21 shows that both surfaces have the same Ra, however, their Material Ratio at a cutting depth of X is quite different (the ratio of their Material Ratio is close to 4).

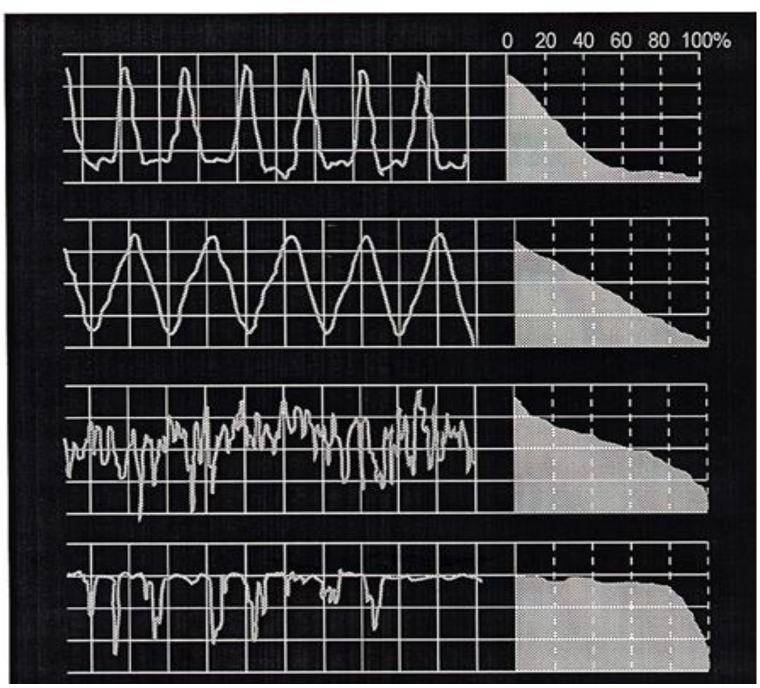


Figure 20. Bearing Area Curves.

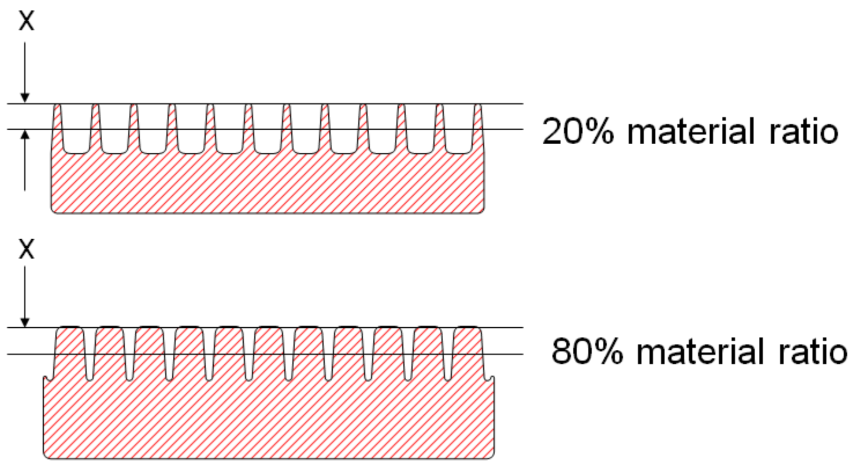


Figure 21. Same Ra surfaces with different Material Ratio

3D Parameters Offer More Details

3D surface parameters readily calculated from 3D topographical measurement data, highlight a surface's waviness, microroughness, wear ability and lubricant retention, as well as the angular orientation of residual machining marks, and much more [12]. In the past decade, significant efforts have been directed towards developing standard worldwide 3D parameters, the result of which is a set of standard "S Parameters" in four general categories: amplitude, spatial, hybrid and functional. Similar to 2D Parameters discussed earlier in this paper, the 3D parameters commonly used now are,

Amplitude Parameters
Based on overall heights,

(1) **Root Mean Square Deviation, Sq-** RMS of height distribution
(2) **Skewness, Ssk-** the degree of asymmetry of a surface height distribution
(3) **Kurtosis, Sku –** the degree of peakedness of a surface height distribution
(4) **Average Height, Sz –** average of ten highest and lowest points.

Spatial Parameters
Based on frequencies of features

(1) **Sds** - Density of Summits,
(2) **Str-** Texture aspect ratio
(3) **Sal –** Fastest decay autocorrelation length
(4) **Std –** Texture direction of surface

Hybrid Parameters
Based on a combination of frequency and height

(1) **SDq** – Root Mean Square Surface Slope
(2) **Ssc –** Mean summit Curvature
(3) **Sdr –** Developed Surface Area Ratio

<u>Functional Parameters</u>

Based on applicability for particular functions

(1) **Sbi** – Surface Bearing Index
(2) **Sci** – Core Fluid retention Index
(3) **Svi** – Valley Fluid Retention Index

Typical applications for various 3D parameters are shown in figure 22.

Function	Amplitude	Spatial	Hybrid	Functional
Bearings	▲	▲	■	▲
Seals	▲	■	▲	▲
Friction	▲	▲	▲	▲
Joint Stiffness	▲	■	■	▲
Slideways	▲	▲	■	▲
Electrical/Thermal Contacts	▲	▲	▲	▲
Wear	▲	▲	▲	▲
Galling	▲	●	▲	▲
Bonding & Adhesion	▲	●	■	▲
Painting & Plating	▲	■	■	▲
Forming & Drawing	▲	▲	■	▲
Fatigue	▲		●	▲
Stress & Fracture	▲		■	▲
Reflectivity	▲	■	▲	▲
Hygiene	▲		■	▲

▲ = Much evidence ■ = Some evidence ● = Little or circumstantial evidence

Figure 22. Shaft Radial Lip Seal [12].

Results and Discussion

The following case studies reflect the very fact why Ra alone is not an indicator of the functional traits of a surface. Additional parameters are required to specify the design and performance intent.

<u>Case Study #1</u>

Figure 23 shows a roller contact bearing mounted on a shaft (tight fit). The shaded region (in red) is the inner seal of the bearing in contact with the shaft. It is imperative that the contact area be as high as possible for the inner seal to not slip ever over the shaft. Traditionally, however, the design/drawing specifies only Ra on the inner surface of the seal. As can be seen in Figure 23 (a) and (b), both conditions delineate to the same Ra value of the surface. However, (b) has clearly more contact area as compared to (a). This is also obvious based on Material Ratio Curve (also known as bearing area curve), that (b) has a much higher bearing area, providing a higher required contact area for the design to work effectively. Ra is often specified and is valuable for monitoring process stability, however, it is high time that all drawings for surface finish use additional parameters that may be needed to monitor for surface function.

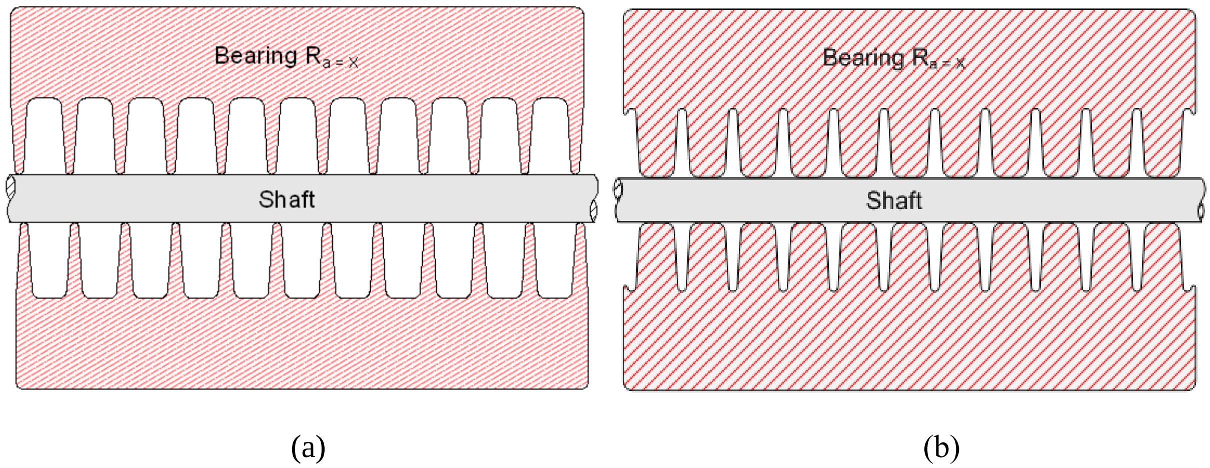


Figure 23. Surface profiles with same Ra, but different BAC

<u>Case Study #2</u>
Figure 24 shows a journal bearing whose surface had a Ra specification earlier. Although inspection resulted in 100% acceptance, some of these bearings seized during operation. Consequently, the design was revised to a lower 0.2Ra, hoping to fully address the issue. It was however, realized that most of the bearings failed (seized) after the design revision. A detailed investigation of profile analysis showed the presence of long wave forms. This poor bearing contact was not quite obvious or visible by measuring Ra. Waviness height (Wt) was subsequently specified to give visibility to this condition. No journals failed following this revision.

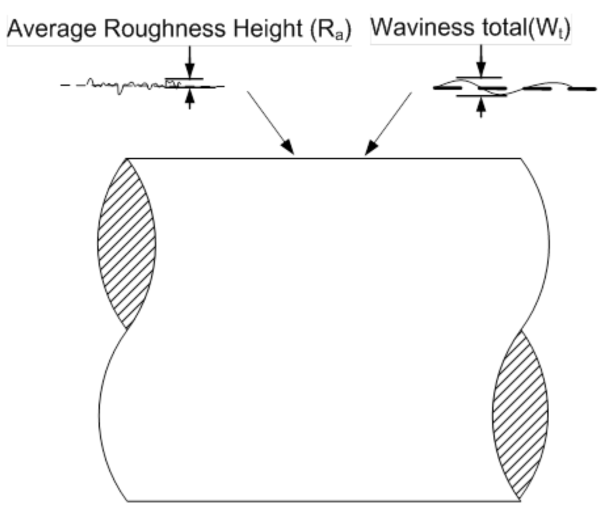


Figure 24. Bearing Journal

<u>Case Study #3</u>
Figure 25 shows radial lip seal on a shaft in fluid flow design. The original design/drawing specified Ra on the shaft-area of the lip seal. However, during inspection it was realized that with

a 0.25 mm cutoff (λc) observed Ra was rejecting parts. Further, lip seal length is shorter than 0.8 mm "default" cutoff. Further studies showed it is important to monitor peak heights Rpm as peaks are abrasive to the lip seal. More elaborate methods of assessing seal surfaces include new approaches to lead angle measurement.

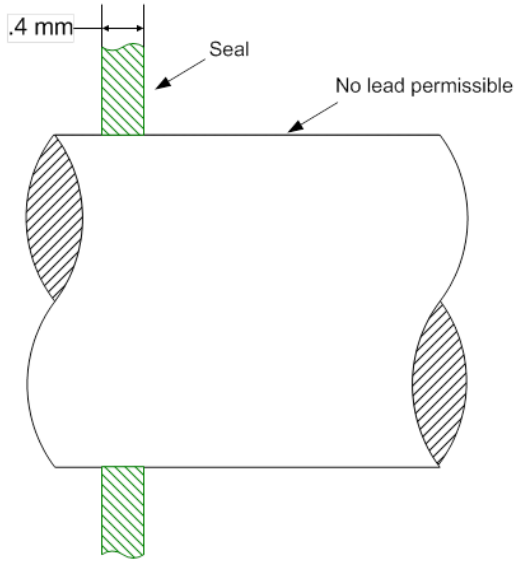
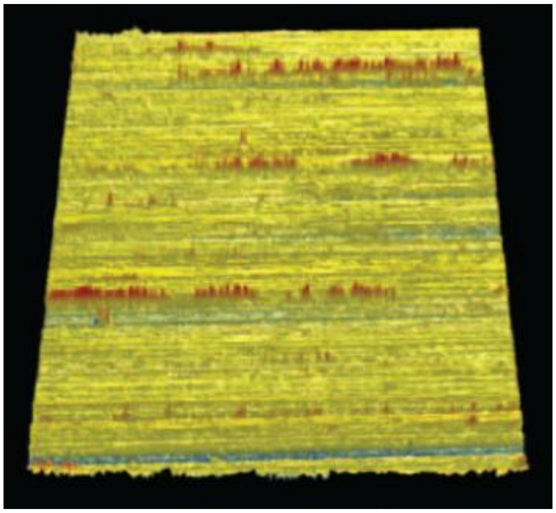
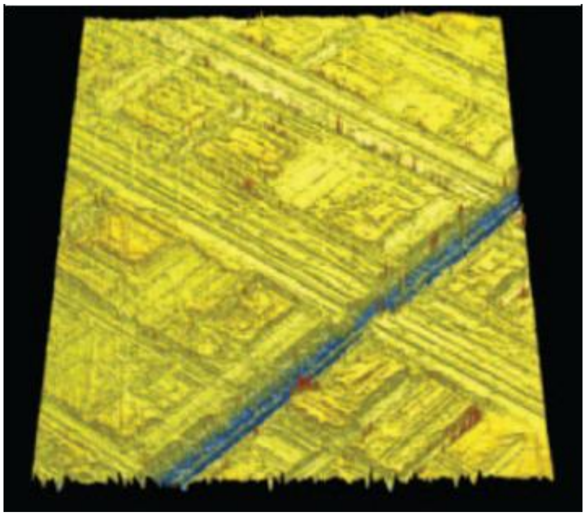


Figure 25. Shaft Radial Lip Seal.

<u>Case Study #4</u>

Figure 26 shows three surfaces from a surface comparator strip generated by grinding, Blanchard grinding and shape turning. *Blanchard grinding, also known as rotary surface grinding,* is used to efficiently remove stock from one side of material with a large surface area. It is a far more economical process than precision *grinding.* All three surfaces were found to have approximately the same Ra (680-750 nm). Yet, the functional traits of these very different surfaces are indistinguishable by Ra. Which surface will wear well? Which will retain fluid? Which will survive a bearing load, or which is susceptible to stress cracking along machining marks? Ra provides no information to answer these questions. [12].





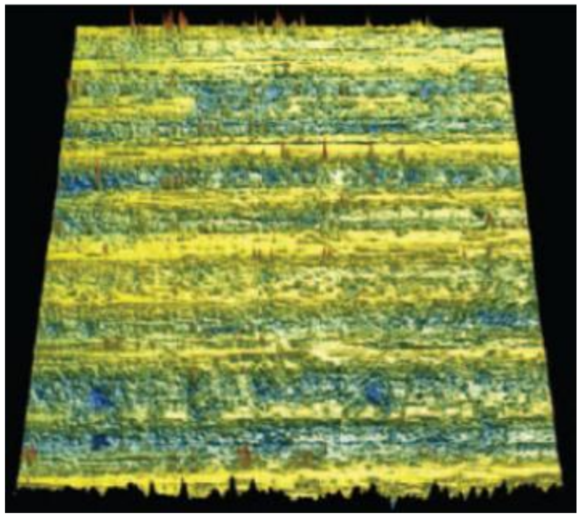


Figure 26. Optical Profiler Images of Surfaces from Grinding, Blanchard Grinding and Shape Turning Processes [12].

Need in Manufacturing/Engineering curriculum and Education Plan

As explained in this article, despite the availability of measurement equipment and literature on several surface quality indicators, Ra remains the sole parameter to be taught in engineering curriculum, and worse, correlated to the functional nature of a surface. Authors believe that it is high time that the discussed surface parameters, tools, filters and mathematical modeling of methods be included in all design, manufacturing and capstone project courses (freshmen through senior year). A better educated workforce would be able to contribute significantly higher to quality tools and advanced metrology. It is an evolutionary process, i.e., standards keep constantly changing; however, it must transition smoothly into the curriculum. It is imperative that course instructors keep up to date with the latest standards, and implement them as short interactive modules. In an ongoing effort, based upon the contents of this paper, the authors have made several instructional modules on surface finish. These modules include power point presentations, ready-to-implement instructor's kit, in-class and homework problems, and well-documented hands-on laboratory exercises. These modules and be readily used in existing mechanical and manufacturing engineering programs, both undergraduate and graduate curricula. Courses that can directly benefit and have strong potential for implementation are Mechanical Design, Machine Design, All courses in Manufacturing Processes, Freshmen, Sophomore and Senior Design courses, Surface Metrology, Precision Engineering, courses in Tribology, friction and wear, etc. As a trial run, at the University of XXXXXXX, a 3-hour course module was implemented in the Junior/Senior Manufacturing Processes course. This included a 1-hour hands-on laboratory exercise. Four of these trial runs have been made since Spring 2016. University of XXXXXXXX has a state-of-the-art Center for Manufacturing Metrology. It houses both Contact (stylus-based) and non-contact (white light interferometry-based 3D surface profiler) surface metrology equipment. The evaluation of the success of this module was based on the metrics shown in Table 1. Results have been very encouraging thus far. The module has been appreciated by our students, more by the graduate students who work full time in industry as they see a direct relevance and impact on their technical skills and knowledge. Additionally, student surveys are being developed that will be included in courses in Spring 2018. Further, a survey will be made for the local industry people whose feedback on implementation of surface finish standards in undergraduate and graduate programs will be sought.

Table 1. Evaluation Plan for the Module on Surface finish

Performance Objectives	Evaluation Instrument	Performance Criteria	Results
Number of courses using Surface Finish Standards	Syllabus	Minimum two courses in curriculum	3 courses
Diversity of SDO's in program	Syllabus	Minimum two SDO's	ASME, ISO
Number of students in courses	Enrollment	25 Per Semester	More than 50 Senior UG More than 30 Grads
Breadth and Depth of Standards Implementation	Student/participation/IAC survey	7 on a scale of 10	9/10 Graduate courses and short courses
Extent of Standards Application	Examination/Projects	3 in a scale of 4	4

Conclusions

1. Authors, via these case studies, discovered that Ra is not necessarily an effective quality screen or an adequate measure for development or problem solving.
2. Things can go wrong in surface finish gaging if one doesn't understand and differentiate different parameters like, Ra, Rq, Rz, etc.
3. Selecting the wrong gage (skidless vs. skidded) can affect accuracy.
4. Also, relying too much on a "default" cutoff filter or selecting the wrong cutoff filter can compromise the results of roughness and waviness parameters.
5. Do not attempt to correlate different and unrelated parameters, especially now when we have more than 100 parameters on surface finish.
6. 3D surface parameters provide more information about a surface than the conventional 2D parameters. This can efficiently aid product design, development and prototyping.
7. It is high time instructors in design, manufacturing and senior capstone design projects include discussion of these surface quality parameters in their courses Bite-size modules (including case studies) dealing with mathematical understanding of surface, cut-off filters, profile and waviness height parameters, spacing, shape and hybrid parameters must be included.

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