Stylus Tip-Size Effect on the Calibration of Periodic Roughness Specimens with Rectangular Profiles

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Abstract

Stylus instruments are widely used for surface characterization. It is well known that the size and shape of the stylus tip affects the measured surface geometry and parameters. In most cases, increasing the tip size decreases the measured *Ra* value because the enlarged tip does not come into contact with the bottom of sharp valleys. However, even when the tip can reach the bottom of the valleys, the tip size can have a significant, and at times counter-intuitive, effect on the measured *Ra* value. In this paper we analyze the effect of stylus tip radius on the measurement of periodic roughness specimens having rectangular profiles with flat valleys. Rectangular profile roughness specimens function as Type C reference specimens described in the ASME B46-2009 and ISO 5436-1:2000 standards. For these profiles, the effect of tip radius on measured *Ra* is affected by the ratio of the peak width to the valley width. If the width of a rectangular profile peak is larger than the profile valley, the measured *Ra* is smaller than the *Ra* of the real surface and decreases with increasing tip sizes. However, if the measured width of a peak is smaller than the measured width of a valley, the measured *Ra* is larger than the *Ra* of the real surface and increases with increasing tip sizes. The effect of tip radius on *Ra* results in a systematic offset. This offset can be larger than the measurement uncertainty, even in cases where the tip radius is smaller than the low-pass digital cutoff filter used to suppress noise and tip radius effects. We show results of theoretical analyses, simulations, and experiments. The results raise questions as to whether the measured surface texture parameters should be corrected for tip-size effects.

Keywords:

surface roughness, roughness average, periodic roughness specimens, rectangular profile, stylus tip, stylus radius

1 INTRODUCTION

It is well known that the size of the stylus tip in surface metrology affects the measured surface geometry and surface roughness parameters. Typically an increase in the size of the stylus tip will result in a reduction in the measured roughness average (*Ra*) due to the tip's inability to contact the bottom of sharp valleys on the surface.

A different type of effect is also possible for periodic roughness specimens with rectangular profiles, also known as 'square wave specimens' and similar to Type C reference specimens [1,2]. When a stylus is traversed over the surface, the width of the stylus tip increases the measured widths of the peaks and decreases the measured widths of the valleys. This skews the calculated *Ra* value causing a systematic offset. The direction of the change in *Ra* depends on the duty cycle of the square wave. If the square wave has wider peaks than valleys, the *Ra* value decreases with increasing tip width, in accord with typical experience on random profile surfaces. If the measured peaks are narrower than the measured valleys, however, the *Ra* value increases with increasing tip width. This is counter-intuitive to someone trained by the more common situation. However, analysis of the phenomenon reveals the mechanics behind the observed differences in *Ra*. The magnitude of the difference between true and measured *Ra* can be quite large, sometimes exceeding uncertainty estimates, which could potentially lead to instrument calibration errors.

This paper explores the effects of stylus tip size when measuring square wave specimens. Results of simulated measurements of mathematical models of square wave surfaces are compared with actual measurements of typical square wave specimens.

2 OVERVIEW

Periodic roughness specimens with rectangular profiles, or square wave specimens (Figure 1), are routinely used in the calibration of roughness measuring instruments [9].

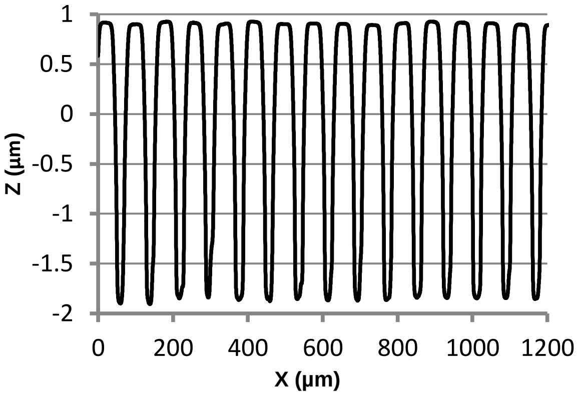


Figure 1: Profile of a typical square wave specimen.

Roughness average (*Ra*) is a widely used parameter to characterize surface roughness [1,3]. Typically a surface reference specimen with a specified *Ra* value and associated uncertainty estimate is used to calibrate, or to verify the calibration of, a surface roughness measuring instrument. The uncertainty estimate should include all known error sources, including those due to the stylus tip that was used to calibrate the specimen. However, the effects of tip radius on the measured *Ra* of square wave specimens are not well known. If they are not included in the uncertainty estimate, this can result in an underestimate of the calibration uncertainty which may then be too small to adequately cover the differences that can be observed. Errors may occur when using the reference specimen to calibrate an instrument, especially when the tip radius used during instrument calibration differs from that used during the specimen calibration.

To analyze the effects of tip radius on the measurement of square wave roughness specimens, we first start with an ideal square wave profile. This profile has a constant peak height offset vertically from a constant valley depth. The lateral transition width between peak and valley is ideally zero, meaning vertical sidewalls. In practice, readily available square wave specimens for surface metrology have sloped sidewalls due to fabrication limitations. On a typical glass specimen fabricated using chemical etching, we measured maximum sidewall slope angles of approximately 30°. However, to understand the effects of tip radius on square wave specimens, we first explore the effects on an ideal square wave profile that has perfect peak widths and valley widths, and vertical side walls (Figure 2). From there, we expand the analysis to include real square wave surfaces.

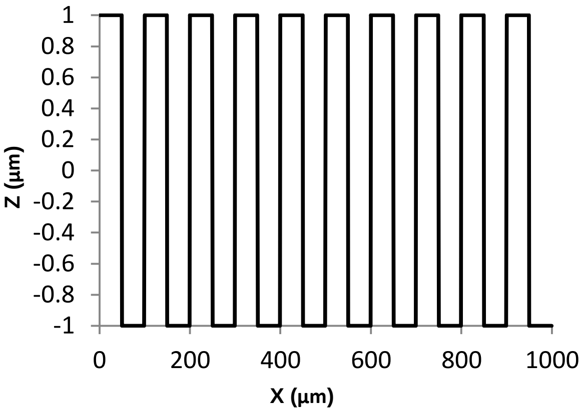


Figure 2: Ideal square wave profile.

In surface metrology, some profile modification is performed before calculation of parameters. A mean line is subtracted from the profile (for primary parameters) or the profile is filtered using a digital Gaussian filter (for roughness parameters) [1,4]. This must be performed before the *Ra* calculation. Afterward, the *Ra* of the digital profile is calculated by taking the absolute value of all digitized points, Z_i, summing them, and dividing by the number of points in the profile, N.

$$Ra = (|Z_1| + |Z_2| + |Z_3| \dots |Z_n|) \,/\, N \qquad (1)$$

The *Ra* of an ideal square wave equals half the vertical height (peak to valley) when the peak width equals the valley width (50 % duty cycle). When the peak width is either larger than or smaller than the valley width, the *Ra* value is reduced. This is due to the mean line shifting up (in the case of wider peaks) or down (in the case of wider valleys). As the mean line shifts, it affects the contribution to the *Ra* value of the peak data points relative to the valley data points. Figure 3 shows the effect on *Ra* as the peak width varies as a percentage of spatial wavelength. At the 50 % duty cycle point (peak width equals valley width), *Ra* is maximized. If the peak width increases or decreases, *Ra* decreases. At the extremes (peak width equals 0 % or 100 % of wavelength), the profile becomes a straight line and *Ra* equals zero.

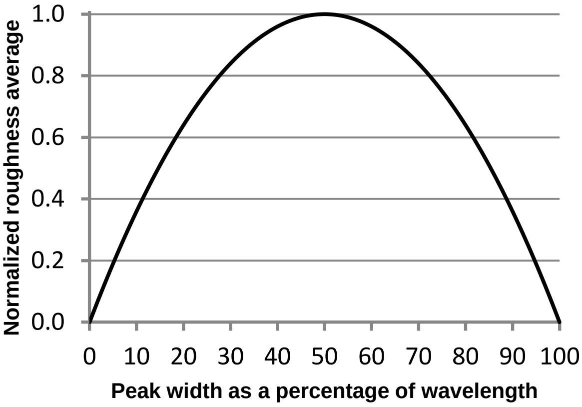


Figure 3: *Ra* of an ideal square wave profile as the peak width is varied relative to total wavelength.

3 STYLUS TIP DILATION EFFECTS

When a surface is measured using a stylus tip, the measured profile is a dilation of the surface geometry by the tip geometry [5,6]. As a round stylus tip traverses the surface, it is in effect sliding a ball of radius *r* over the surface features. The resulting **measured surface** is the path of the stylus tip as it traverses the surface (Figure 4). When peaks are encountered, they are effectively widened by the stylus tip's nonzero size. For a square wave specimen, this will widen the peaks and narrow the valleys. In extreme cases, the tip radius may be so large that it is not able to touch the bottom of the valleys. As mentioned earlier, this effect is well known in surface metrology and is not a point of discussion in this paper. Instead, the effects described here are due to the widening of the peaks and narrowing of the valleys.

In addition to the radius of the tip affecting the measured profile, the conical flank of the tip may also encounter the surface. This happens when the magnitude of the surface slope exceeds that of the tip flank, provided the peak to valley height is large enough. A typical stylus tip has a 90° included angle, although some are sharper (e.g., 60°). Therefore, if the slope of the surface exceeds 45° (for a 90° tip), and the peak to valley height is large enough, the cone flank will touch the surface (Figure 4). This often occurs in simulations involving perfect square wave profiles. However, for actual square wave roughness specimens, the sidewall slope angles are much smaller. In the majority of cases, the tip radius is always in contact with the surface.

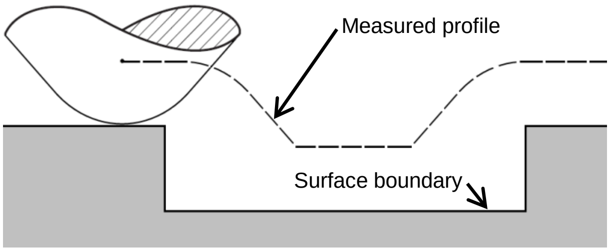
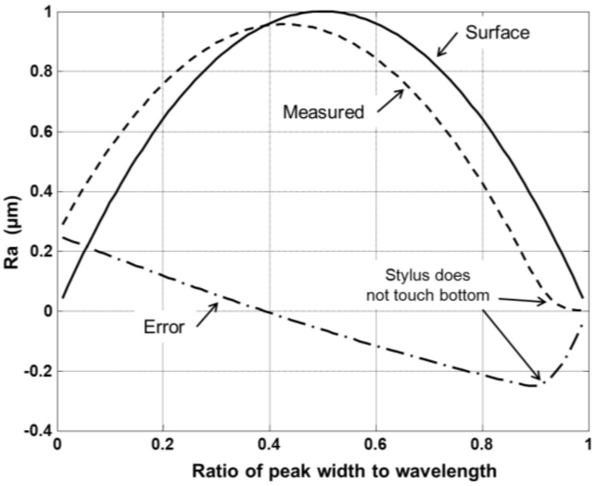


Figure 4: Stylus tip path over a square wave surface.

Figure 5 shows the effect on *Ra* of a stylus tip with nominal radius of 2 µm and a 90° cone angle as it traverses an ideal square wave surface having a peak-to-valley height of 2 µm and a wavelength of 50 µm. The graph shows how *Ra* changes as a function of the ratio of peak width to wavelength. The curve showing the *Ra* of the **measured surface** is shifted to the left of the curve showing the *Ra* of the **real surface**. This is because the width of the tip increases the peak widths and reduces the valley widths. For this particular scenario, the *Ra* of the **measured surface** will equal the *Ra* of the **real surface** at approximately 40 % duty cycle. Varying the tip size, wavelength and peak-to-valley height will change the crossover point.

The tip effect on *Ra* becomes more significant as the dissimilarity between the widths of the peaks and valleys increases (Figure 5; right and left regions). The sign of the offset in the measured *Ra* depends on the ratio of measured peak widths to valley widths. Larger measured peak widths than valley widths result in a negative error (reduction in *Ra*). For narrower measured peak widths than valley widths, the error is positive (increase in *Ra*). Initially, this may seem counter-intuitive. However, the analysis shows the nature of the change in *Ra*. In general, the magnitude of the error increases with increasing tip size or increasing surface peak-to-valley height. At the far right in Figure 5 is the area at which the stylus is no longer able to touch the valleys, as the valley widths become narrower than the tip.

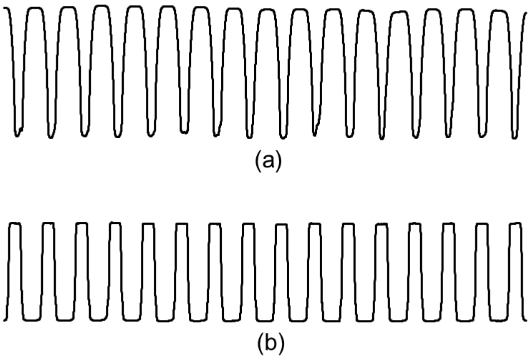


- Stylus radius: 2 µm (90 degree cone angle)
- Wavelength: 50 µm
- Peak to valley height: 2 µm (theoretical square wave)

Figure 5: Error in *Ra* of a theoretical square wave as a function of the ratio of peak width to wavelength.

4 MEASUREMENT RESULTS

Profiles of square wave roughness specimens were measured, and the results support the theoretical analysis. Two measured specimens are highlighted here: one with larger peak widths than valley widths (Figure 6a) and the other, with larger valley widths than peak widths (Figure 6b). Measured profiles include the effect of dilation by the stylus tip (nominal 2 µm radius). The best estimate of the actual (real) surface profile is obtained by eroding the tip shape from the measured profile [5,6]. In both cases, there were significant differences in *Ra* between the measured surfaces and the (nominally, i.e., reconstructed) real surfaces. For the surface with wider peaks than valleys, the *Ra* of the measured profile is smaller than the *Ra* of the eroded profile (i.e., a negative measurement error). For the surface with wider valleys than peaks, the *Ra* of the measured profile is larger than the *Ra* of the eroded profile (i.e., a positive measurement error). In both cases, the *Ra* error is significant (more than 1.5 %) and ordinarily represents a systematic offset large enough to exceed typical expanded measurement uncertainties.



(a)

(b)

Figure 6: Two independently measured square wave surfaces having wider peak widths (a), and wider valley widths (b).

Figure 7 shows a magnified view of one valley of the wide peak specimen. The solid line is the measured profile. The dashed line is the profile after application of the erosion filter using a conical tip shape with a nominal radius of 2 µm. Both profiles were also filtered with a digital Gaussian filter having a long wavelength cutoff of λc = 0.25 mm and a short wavelength cutoff of λs = 2.5 µm. When the measured profile is eroded (i.e., providing ideally a profile of the **real surface**), the valleys become slightly wider. This decreases the mean line of the profile. As a result, the eroded profile increases in *Ra* value. The measured profile has an *Ra* of 0.963 µm. The eroded profile increases in *Ra* to 0.978 µm. This corresponds to a negative error in the measured *Ra* of 0.015 µm or approximately 1.5 %.

Figure 8 shows the specimen having wider valley widths. The solid line is the measured profile and the dashed line is the eroded profile obtained using a 2 µm tip radius. Again, both profiles are filtered using a digital Gaussian filter having a long wavelength cutoff of λc = 0.25 mm and a short wavelength cutoff of λs = 2.5 µm. In this case, applying the erosion filter (i.e., providing ideally a profile of the **real surface**) causes the peaks to become narrower which decreases the mean line of the profile. As a result, the eroded profile reduces in *Ra*

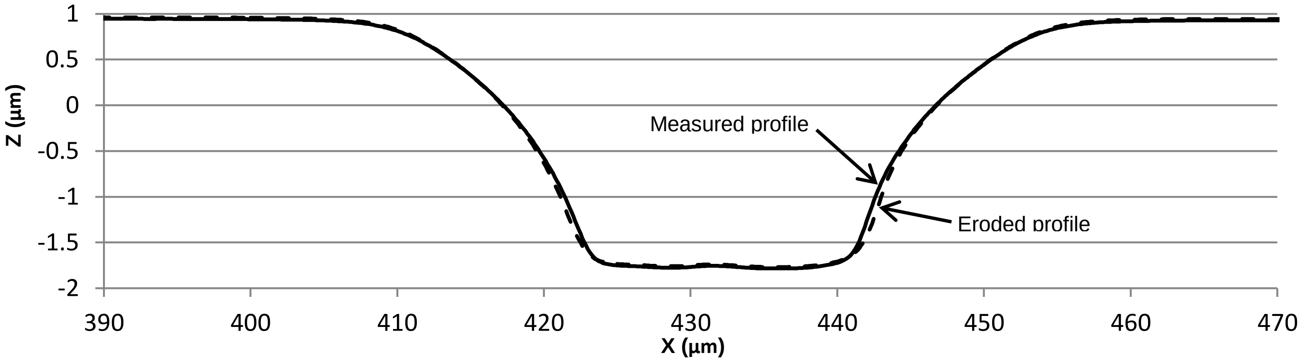


Figure 7: Magnified profile of square wave surface with wide peaks. Comparison of measured profile (solid line) with eroded profile (dashed line).

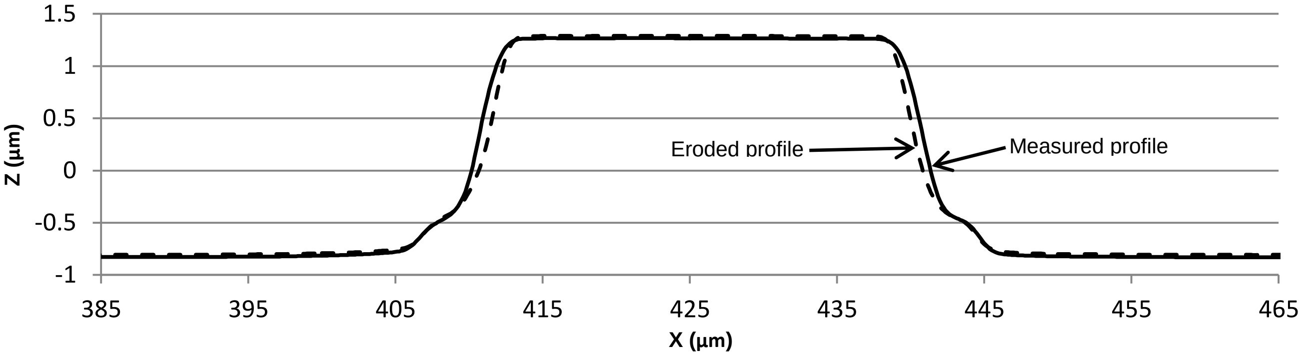


Figure 8: Magnified profile of square wave surface with wide valleys. Comparison of measured profile (solid line) with eroded profile (dashed line).

value. The measured profile has an *Ra* of 0.922 µm. The eroded profile decreases in *Ra* to 0.905 µm. This corresponds to a positive error in the measured *Ra* of 0.017 µm or approximately 1.9 %.

While these errors are much smaller than the errors obtained in the modeling of a perfect square wave, they still represent a significant offset. Typical calibration specimens can have expanded uncertainties of +/- 0.5 % to 1 %. Having an offset error of 1.5 % solely due to the stylus tip interaction with the surface can cause significant problems in performing instrument calibrations when using different stylus tip radii. This also shows that there can be significant differences in *Ra* due to the stylus tip even when the tip radius is smaller than the low-pass digital cutoff filter (short wavelength cutoff, λs) which is normally used to suppress noise and tip radius effects. Note that the two profiles discussed above are not directly compared. Rather, they are used to demonstrate how a positive or negative error in the measured *Ra* can be made depending on the duty cycle of the profile (i.e., wider valleys than peaks, or wider peaks than valleys).

5 INTERNATIONAL STANDARDS

An important question is whether or not to apply tip correction to surface profiles. In the past, commercially available stylus instruments did not have the resources to apply advanced filters that are computationally intensive. However, with recent advances in computing power, these types of filters are now available on stylus instruments as well as on external software analysis packages. Several measurement techniques have been developed to obtain the stylus radius or stylus shape [10].

The answer to the question depends on the definition of the measurand; i.e., whether the measurand refers to the real surface, the mechanical surface [8], or the surface profile obtained with a specified nominal tip size. In our opinion tip correction, if available, should be applied in the first two cases, and may be necessary in the third case when using a different tip size than specified. In the third case, tip correction is achieved by first eroding the measured profile with the tip geometry used during measurement followed by dilating the profile with the nominal tip geometry.

The surface profile dilation due to the stylus tip creates a systematic offset (or error) in the calculated roughness parameters. For the purpose of comparing measurement results with those performed in other laboratories, where different styli may be in use, the roughness of the **real surface** is desired. This is better approximated by minimizing the effects of the stylus tip by using morphological filtering than by analyzing the (differently) dilated measured surfaces. However, it should be noted that, for many surfaces, even the most advanced filter cannot yield a perfect reconstruction of the actual surface, as the finite size of the stylus tip results in some loss of information [6].

There are several international standards that describe how to deal with known systematic offsets and/or differences between the **measured surface** and the **real surface**. Paragraph 3.2.4 of the GUM [7] states:

> *'It is assumed that the result of a measurement has been corrected for all recognized significant systematic effects and that every effort has been made to identify such effects.'*

This clearly implies that the significant systematic effects due to the stylus tip should be corrected if the measurand refers to the **real surface**.

The ISO standard, ISO 25178-2:2012 [8], defines the **mechanical surface** as the:

> *'boundary of the erosion, by a spherical ball of radius r, of the locus of the centre of an ideal tactile sphere, also with radius r, rolled over the skin model of a workpiece.'*

This describes the process of eroding a spherical model-stylus from a measured (modeled by rolling, which is equivalent to dilation) surface to achieve a profile that best represents the **real surface**.

6 CONCLUSIONS

In this paper, the effects of the stylus tip on periodic roughness specimens with rectangular profiles have been described. In the measurement of square wave roughness specimens with wider peaks than valleys, a larger tip radius will result in a smaller *Ra* value. However, for specimens with wider valleys than peaks, just the opposite can occur. In some cases, the differences in *Ra* can be significant enough to exceed established uncertainty estimates.

7 REFERENCES

[1] ASME B46.1-2009, 2010, Surface Texture – Roughness Waviness and Lay, ASME, New York.

[2] ISO 5436-1:2000, 2000, Geometrical Product Specifications (GPS) – Surface texture: Profile method; Measurement standards – Part 1: Material measures, ISO, Geneva.

[3] ISO 4287:1997, 1997, Geometrical Product Specifications (GPS) – Surface texture: Profile method – Terms, definitions and surface texture parameters, ISO, Geneva.

[4] ISO 11562:1996(E), 1996, Geometrical Product Specifications (GPS) – Surface texture: Profile method – Metrological characteristics of phase correct filters, ISO, Geneva.

[5] Muralikrishnan, B., Raja, J., 2009, *Computational Surface and Roundness Metrology*, Springer-Verlag, UK.

[6] Villarrubia, J.S., 1997, "Algorithms for scanned probe microscope image simulation, surface reconstruction, and tip estimation," J. Res. NIST, 102, 4, pp. 425-454.

[7] Guide to the Expression of Uncertainty in Measurement (GUM), 1993, BIPM, ISO, p5.

[8] ISO 25178-2:2012(E), 2012, Geometrical Product Specifications (GPS) – Surface Texture: Areal – Part 2: Terms, definitions and surface texture parameters, ISO, p2.

[9] Song, J., Vorburger, T., 1991, "Standard reference specimens in quality control of engineering surfaces." J. Res. NIST, 96, 3, pp. 271-289.

[10] Song, J., Vorburger, T., 1997, "Measurement Comparison of Stylus Radii," *Proc. International Conference on Precision Engineering*, Taipei, Taiwan, pp. 823-828.