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The Effect of Tip Size on the Measured *Ra* of Surface Roughness Specimens with Rectangular Profiles

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ABSTRACT
When measuring rectangular and trapezoidal profile roughness specimens, the stylus tip increases the measured profile peak width and decreases the measured valley width. This can cause either an increase or a decrease in the apparent roughness average *Ra*, depending on the tip size and the ratio of peak width to valley width. Sometimes the change is larger than the combined measurement uncertainty from other sources. This raises the question as to whether measured surface parameters should be corrected for the effect of tip size.

KEYWORDS: Surface metrology, roughness average, roughness calibration, rectangular profile, stylus radius, Type C roughness specimen.

1. INTRODUCTION

Periodic profile roughness specimens are defined as Type C roughness specimens in the ASME B46-2009 [1] and ISO 5436-1:2000 standards [2] for the calibration of stylus instruments. Examples are specimens with triangular, sinusoidal, arcuate, rectangular or trapezoidal profiles. It is well known that the size and shape of the stylus tip affect the measured surface geometry and roughness parameter values. For the measurement of engineering surfaces with fine surface texture, increasing tip size may decrease the measured *Ra* value because the larger tip does not contact the bottom of narrow valleys. However, for the calibration of Type C roughness specimens with wide profile bottoms, such as specimens with arcuate, rectangular or trapezoidal profiles, the main effect of tip size is to increase the measured peak width and decrease the measured valley width. This may have a significant, and at times counter-intuitive, effect on the measured *Ra* value. For example, an arcuate profile roughness specimen measured with a 0.4 μm tip radius showed an *Ra* value of 1.260 μm (Fig. 1a). When the tip radius was increased to 5 μm, however, the *Ra* value did not decrease, but rather increased to 1.332 μm (Fig. 1b)) [3]. The expanded uncertainty of both measurements was estimated to be less than 1.5 % *Ra*. The *Ra* difference (0.072 μm, or 5.7 % *Ra*) was almost 2.7 times as large as the combined uncertainty arising from other sources.

2. CALIBRATION OF RECTANGULAR AND TRAPEZOIDAL PROFILE SPECIMENS

The same effect may occur when measuring rectangular and trapezoidal profile roughness specimens, which are among the most widely used Type C specimens for the calibration of stylus instruments. For a given rectangular or trapezoidal profile with amplitude *A* and wavelength L (Fig. 2a), the maximum *Ra* value

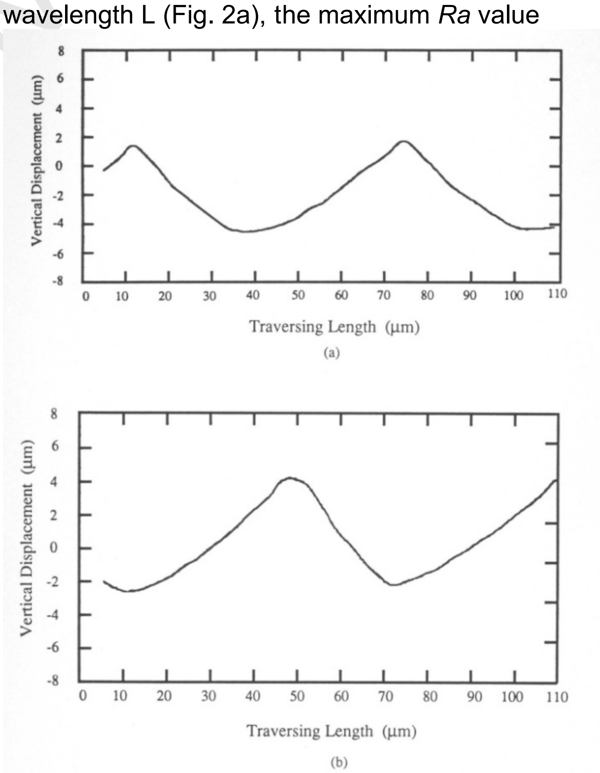

Figure 1. The peak widths of an arcuate profile specimen are enlarged by increasing the stylus radius from 0.4 μm (a) to 5 μm (b). The Ra value increased from 1.260 μm (a) to 1.332 μm (b).

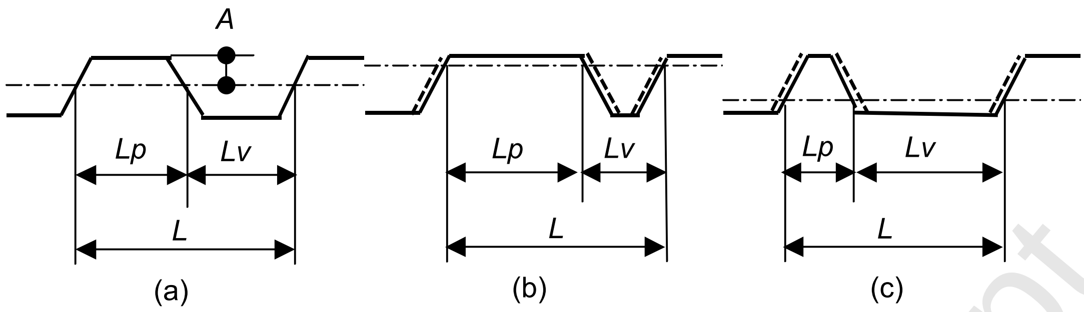

Figure 2. For a trapezoidal profile specimen with amplitude A and wavelength L (Fig. 2a), the maximum roughness Ra value occurs when the peak width Lp equals the valley width Lv or Lp/L = 0.5 (see Fig. 2a).

occurs when the peak width *Lp* equals the valley width *Lv.* For a rectangular profile, the respective *Ra* equals the profile amplitude A: *Ra*(max) = *A*. Either wider (*Lp* > *Lv*, Fig. 2b) or narrower (*Lp* < *Lv*, Fig. 2c) peaks result in a lower *Ra* value. The difference depends on the ratio of *Lp*/*L*. The *Ra* decreases if this ratio increases or decreases relative to 0.5.

For the calibration of rectangular and trapezoidal profile roughness specimens, the measurement error in *Ra* depends on the tip size and profile shape. If the profile peak width is larger than the valley width (*Lp/L > 0.5,* Fig. 2b), the tip size increases the *Lp*/*L* ratio further (see the dashed lines in Fig. 2b), which decreases the measured *Ra* value. On the other hand, if the peak width is significantly smaller than the valley width (*Lp/L < 0.5,* Fig. 2c), the tip size moves the ratio *Lp/L* towards 0.5 (see the dashed lines in Fig. 2c), which increases the measured *Ra* value. When the peak and valley widths of the specimen are significantly different, the *Ra* offset caused by the tip size can be significant.

3. TIP SIZE EFFECT

Figure 3 shows a simplified scheme to estimate the tip size effect for a rectangular profile specimen. The solid line shows a specimen with peak width *Lp* and valley width *Lv*. We start with a cylindrical stylus with radius *r* and a flat end form, allowing the main features of the tip size effect to be explained with simple equations. Because of the tip radius *r*, the measured peak width is increased to *Lp*′ = *Lp* + 2*r*; and the valley width *Lv* is decreased to *Lv*′ = *Lv* − 2*r*. We determine a horizontal mean line by the method of least squares. Then the *Ra* value can be calculated by moving the profile mean line up or down so that the areas above and below the mean line are equal. Then the distances Pv of the mean line to the profile valley floor and Pp of the profile top to the mean line are:

$$Pv = \frac{Pt\ (Lp + 2r)}{L}, \qquad (1)$$

$$Pp = \frac{Pt\ (Lv - 2r)}{L}, \qquad (2)$$

and Ra is given by

$$Ra = \frac{Pp\ (Lp + 2r) + Pv\ (Lv - 2r)}{L}$$

$$= 2P_t(1-\alpha)\alpha + \frac{4P_t}{L}(1-2\alpha)r - \frac{8P_t}{L^2}r^2 \qquad (3)$$

Where *Pt* is profile height, *Pt* = *Pp* + *Pv, and* $\alpha = L_p/L$. The last two terms in the expression for *Ra* represent the errors introduced by the probe radius *r*.

Based on Eq. 1 to 3, Fig. 4 shows the calculated results for the *Ra* values of a rectangular profile specimen as a function of the peak width ratio *Lp*/*L,* assuming the profile height *Pt* is 2 µm, the profile period *L* is 80 µm, and the radius *r* of the cylindrical tip is 2 µm. It can be seen that when

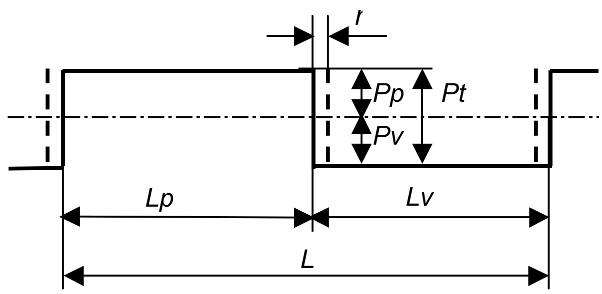

Figure 3. Tip size effect on a rectangular profile specimen.

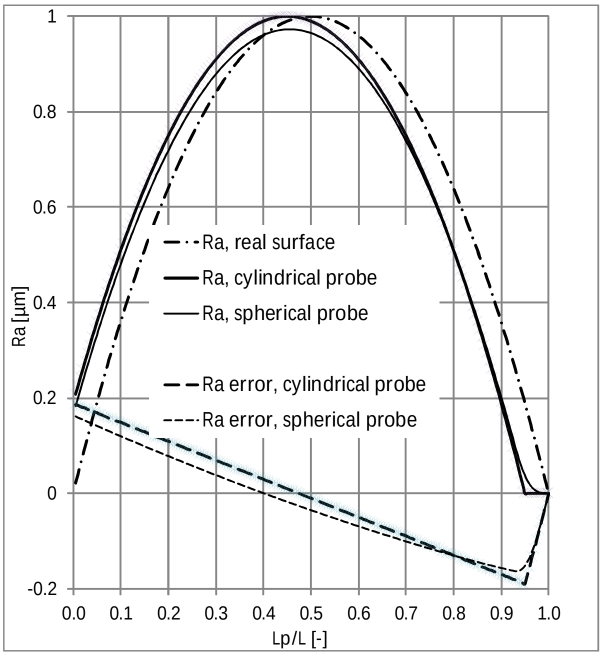

Figure 4. Effect of probe tip radius on the measured Ra value of a rectangular profile for various peak width ratios Lp/L, assuming Pt = 2 μm, L = 80 μm, and r = 2 μm. The spherical probe has a cone angle of 90º.

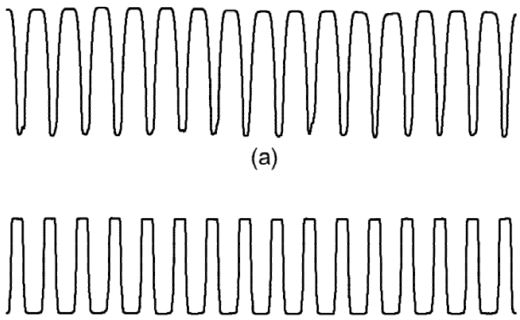

Figure 5: Two rectangular profile roughness specimens having wider peak widths (a), and wider valley widths (b).

the peak width ratio *Lp*/*L* is equal to 0.45, or *Lp* = *L*/2 – 2*r* = 36 μm, the *Ra* for the cylindrical probe achieves the maximum value of 1 μm (0.5 *Pt*). Either a decrease or increase of the profile peak width *Lp* from that point will cause a decrease of the *Ra* value. For the real surface, the maximum *Ra* value occurs when *Lp/L* equals 0.5. In general, the resulting error in the measured *Ra* becomes more significant when the profile peak width ratio *Lp/L* is more extreme i.e., closer to zero or *(L-2r)/L*) and when the ratio *r/L* of probe radius to wavelength increases, as shown in Eq. 3. For comparison, Fig. 4 also shows the effect of a more realistic cone-shaped spherical probe with 2 μm radius and 90° cone angle. The effects caused by the corner rounding and inclined side wall of the cone-shaped spherical probe on the *Ra* measurements can be seen.

4 MEASUREMENT RESULTS

Rectangular profile roughness specimens were measured to support the numerical analysis. Two measured specimens are highlighted here [4]: one with larger peak widths than valley widths (Fig. 5a) and the other with larger valley widths than peak widths (Fig. 5b). The measured profiles include the effect of dilation by the stylus tip (nominally a conical tip with 2 μm radius and 90° cone angle). The best estimate of the real surface profile is obtained by eroding the tip shape from the measured profile using morphological filters [5, 6]. For both specimens, there were significant differences in *Ra* between the measured profiles and the reconstructed profiles. 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 relative error in *Ra* is more than 1.5 %, exceeding the combined expanded uncertainty from other sources. Changes in measured *Ra* are significant even for a modest change in tip radius–for example, from 2 μm to 1.5 μm. Detailed measurement and simulation results can be found in Ref. 4.

5. DISCUSSION

The tip size affects *Ra* measurements not only for calibration of rectangular and trapezoidal profile roughness specimens, but also for measurements of actual engineering surfaces. Furthermore, tip size affects almost all the surface parameters to different extents, some less than *Ra*, some considerably more. That raises a general question in surface metrology: should the measured surface parameters be corrected for the tip size effect? According to the GUM [7], correction is required for any significant systematic effects in measurement results:

> *It is assumed that the result of measurement has been corrected for all recognized significant systematic effects and that every effort has been made to identify such effects.* [7]

Therefore, the answer to the above question depends on the definition of the measurand. Correction is not required if the measurand is the *Ra* of the profile obtained using a tip with a stated radius. However, if the measurand is the *Ra* of the real surface or the mechanical surface, correction is required if the resulting error is significant. In the ISO 25178-2:2012 standard [8], the “mechanical surface” is defined as

> *Boundary of the erosion, by a spherical ball of radius r, of the locus of the center of an ideal tactile sphere, also with radius r, rolled over the skin model of a workpiece.* [8]

This implies that correction should be made for the effect of tip size when the measurand, such as *Ra*, is a property of the mechanical surface. Additionally, since the mechanical surface is by the above definition generally a function of the size of the stylus tip radius, that radius should be specified for any surface measurement.

Many laboratories do not use tip size correction when reporting surface roughness measurements. In some international comparisons, tip size may be a major contributor to significant measurement differences. In order to achieve measurement agreement in both roughness specimen calibrations and engineering surface measurements using different tip sizes, the authors suggest that tip size corrections should be performed by eroding the tip shape from the measured profile using morphological filtering according to ISO 25178-2:2012 [8]. Even so, errors in tip radius and tip form errors can limit the measurement agreement between laboratories. If there is a large uncertainty for tip size measurement, or if the nominal tip size with a large tolerance range is used, an uncertainty component caused by the tip size effect must be included in the uncertainty budget of the surface measurement.

Significant differences were also found in surface measurement comparisons using random profile roughness specimens with *Ra* ranging from 0.01 μm to 0.1 μm [9, 10]. It was suggested that the effect of tip size differences was largely responsible for the observed differences in *Ra* [3]. The quality control of smooth engineering surfaces (*Ra* < 0.1 μm) becomes increasingly important, not only because of their important engineering functions, but also their high production costs. NIST is developing high-precision, random-profile roughness specimens as a Standard Reference Material (SRM) to support smooth engineering surface measurements in industry. The project includes the development of a tip size correction procedure for measurements of smooth engineering surfaces with random profiles.

6. SUMMARY

For the calibration of Type C roughness specimens with wide profile bottoms, such as specimens with arcuate, rectangular or trapezoidal profiles, the main effect of tip size is the increase of peak width and decrease of valley width. This may have a significant, and at times counter-intuitive, effect on the measured *Ra* value. The resulting systematic offset can be larger than the reported measurement uncertainty. We recommend correction of the tip size effect when reporting properties of the real or mechanical surface or when comparing measurements obtained with different tip sizes. Further, stylus tip geometry should be measured and characterized on a regular basis and the tip size should be reported for any stylus-based surface topography measurement. The uncertainty budget may have to include a component that addresses uncertainties in tip geometry.

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