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Technical note

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.

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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 a *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 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 toward 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.

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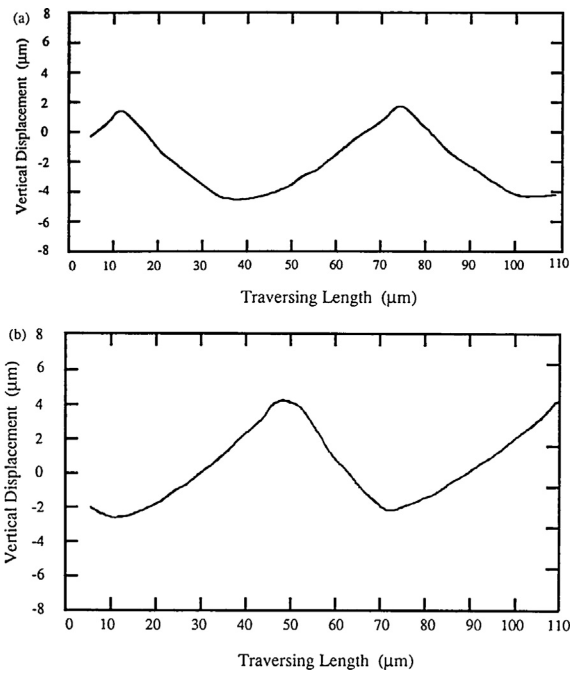

Fig. 1. The peak widths of an arcuate profile specimen are enlarged by increasing the stylus radius from 0.4 μm (a) to 5 μm (b). The *Ra* value increased from 1.260 μm (a) to 1.332 μm (b).

3. Tip size effect

Fig. 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 $Lp' = Lp + 2r$; and the valley width *Lv* is decreased to $Lv' = Lv - 2r$. Assuming a mathematical mean line can be used instead of the least square fitted profile mean line, 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:

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

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

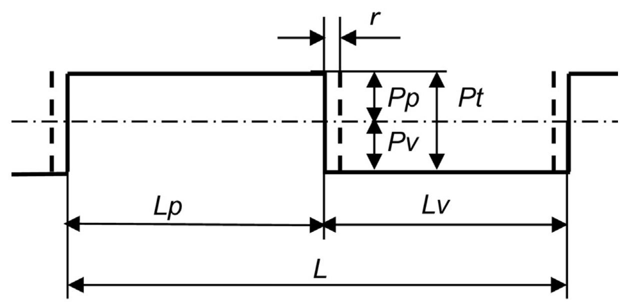

Fig. 3. Tip size effect on a rectangular profile specimen.

and *Ra* is given by

$$Ra = \frac{Pp(Lp + 2r) + Pv(Lv - 2r)}{L} = 2P_t(1 - \alpha)\alpha + \frac{4p}{L}(1 - 2\alpha)r - \frac{8P_t}{L^2}r^2$$

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 Eqs. (1)–(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 the peak width ratio Lp/L is equal to 0.45, or $Lp = L/2 - 2r = 36$ 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. This effect becomes more significant when the profile peak width *Lp* is extremely wide or narrow. 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 pro-

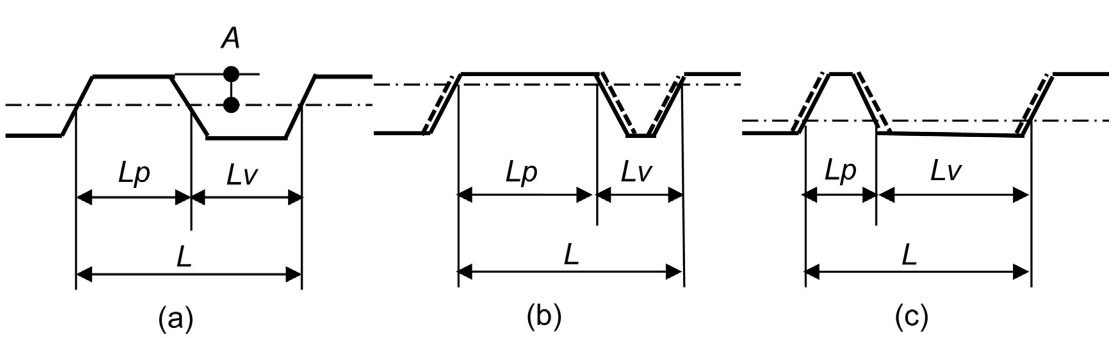

Fig. 2. For a trapezoidal profile specimen with amplitude *A* and wavelength *L* (a), the maximum roughness *Ra* value occurs when the peak width *Lp* equals the valley width *Lv* or $Lp/L = 0.5$ (see (a)).