Good Practice Guide No 1 EMPIR project MicroProbes

Calibration of tip radius of fast microprobes on the machine

Min Xu, Zhi Li, Uwe Brand

Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, D-38116 Braunschweig, Germany

In the EMPIR project MicroProbes, piezoresistive silicon microprobes were developed for high-speed roughness measurements and mechanical property measurements. Because of tip-sample dilation effect, the microprobe tip geometry deviation leads to an increased measurement uncertainty. If the form and size of the tip are known, tip dilation could be corrected.

Tip characterizers are artefacts with specially designed surface features for tip characterization. This Good Practice Guide introduces the 2D tip form characterization methods using tip characterizers on the machine. It compares the applications of different tip characterizers and helps users to select appropriate characterization methods.

1. Introduction

Profiles and images taken with a tactile measurement instrument are geometric dilation results of the artefact surface feature and the tip geometry. Tip dilation directly affects the measurand such as the surface roughness and is a major source of uncertainty [1]. Therefore, the tip geometry knowledge is demanded to improve the measurement accuracy.

Tip characterizers are artefacts with specially designed surface features for tip characterization [2,3]. The tip characterization with a tip characterizer can be performed on the machine and is especially convenient to evaluate the tip form variation if the tip is abraded during the measurement.

The tip form can be expressed as two-dimensional (2D) and three-dimensional (3D) tip form. 2D tip form is the tip outer contour in the traverse direction. 3D tip form means the complete outer surface of the tip. Since profile roughness measurements are mainly affected by the 2D tip form, this guide focuses on the 2D tip form characterization with tip characterizers.

A conical or pyramidal tip is often defined by two parameters: tip radius *r* and opening angle θ (or cone angle), as shown in Fig. 1. The tip end of the 2D tip form is assumed to be circular. Tip radius is the radius of the fitted circle. Opening angle, also called cone angle, is the angle of the fitted cone.

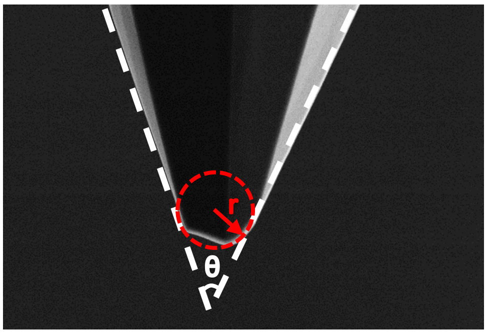


Figure 1 The tip radius r and opening angle ϑ.

2. 2D tip form characterization with tip characterizers

The tip characterizers are classified by their surface structures. The most often used surface structures for tip characterization are rectangular structures, razor blade structures and wedge 2D-radius structures. In the following, the 2D tip form characterizations with the above mentioned structures are introduced in detail.

2.1 The 2D rectangular standard

On a rectangular standard, the rectangular edge with a nm-range radius can characterize the tip radius, and the vertical side wall can characterize the tip opening angle. Rectangular structures are divided into rectangular ridges and rectangular grooves (see Fig. 2).

Figure 2 2D rectangular structures.

With the rectangular ridge structure, the 2D tip form is acquired through subtracting the width of the rectangular ridge from the measured profile and combing the left and right part of the profile. Fig. 3 indicates the imaging procedure of a rectangular ridge structure with the width *W* and the height *H*. The measured profile is the trace of the tip apex (the dashed line). The tip at different positions are drawn with dotted lines. Fig. 4 depicts the procedure of the tip form characterization using a rectangular ridge structure.

With a rectangular groove structure, the tip form can be drawn through choosing the measured profile segment with the width of the groove and switching the left and right part of the deepest position**.** Fig. 5 shows the imaging procedure of a rectangular groove structure with the width W and the height H. Same as above, the measured profile is the trace of the tip apex, drawn with the dashed line. The tip form at different positions is shown with dotted lines. Fig. 6 draws the procedure of the tip form characterization using a rectangular groove structure.

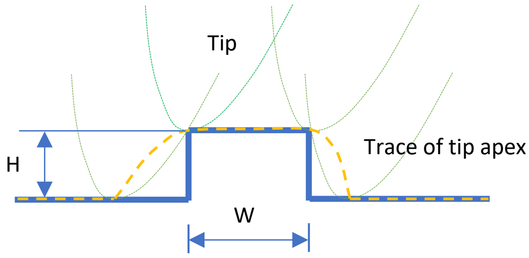


Figure 3 Imaging a rectangular ridge structure.

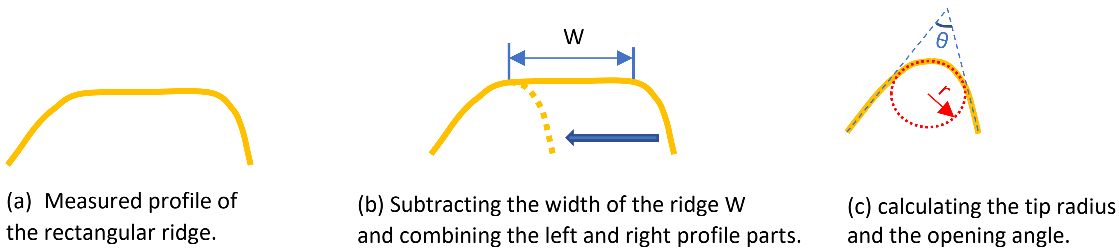


Figure 4 Characterizing the 2D tip form using a rectangular ridge structure.

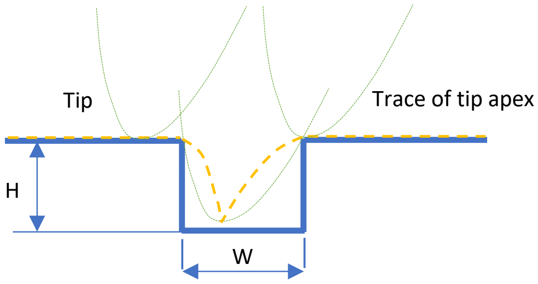
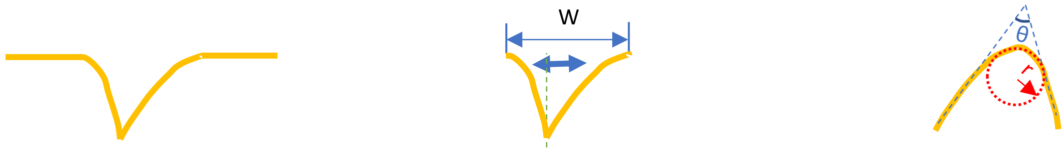


Figure 5 Imaging a rectangular groove structure.



(a) Measured profile of the rectangular groove.

(b) Choosing profile segment with the groove width W, dividing the profile from the deepest position, and switching the left and right profile.

(c) calculating tip radius and the opening angle through fitting.

Figure 4 Characterizing the 2D tip form using a rectangular groove structure.

In practice a comb-shaped standard including both rectangular ridges and grooves structures is usually used as a tip characterizer. PTB developed a comb-shaped tip characterizer named TSPN. As shown in Figure 7, The ridges are 3 µm wide and the grooves are 2 µm deep. The widths of the grooves vary from 0.1 µm to 3.0 µm. Grooves of different widths can characterize tips of various radii and heights.

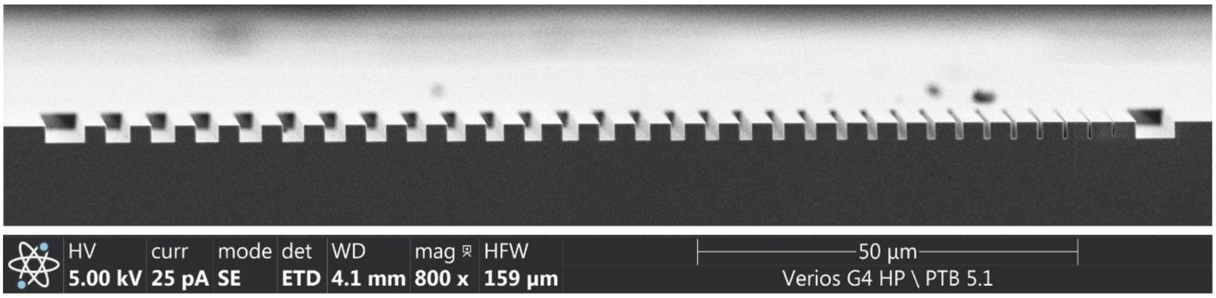


Figure 5 Cross section of PTB's comb-shaped tip characterizer TSPN

From the tip form characterization procedures described above, it can be seen, determining the rectangular structure edge positions is important. The edge position determination yields the tip apex and the width of the tip. It decides on the uncertainties of the characterization.

The gradient of the profile *gr(x)* is often used as the criterion in determining the edge positions:

$$gr(x) = \frac{dz(x)}{dx} \qquad (1)$$

where x is the abscissa and *z(x)* is the measured profile.

Two methods, the gradient range method and the structure width method, are often adopted to determine the edge positions. Both methods assume the gradients of the measured profile on the ridge top are constant and the gradients vary at the edge and the groove. The edges of the rectangular structures are searched according to the variation of the gradients.

In gradient range method, the gradients on the ridge top are considered within the range $gr_t \pm \Delta gr$. The profile segment with the gradients out of the range is determined to be the edge and groove, as shown in Fig. 8.

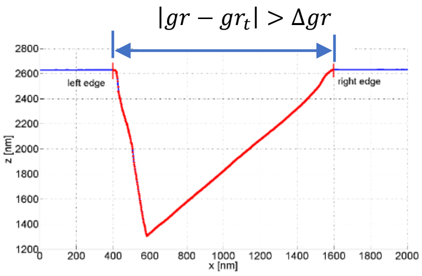
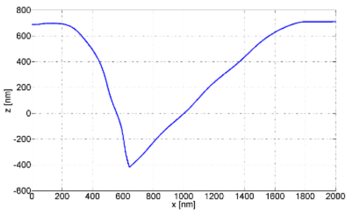
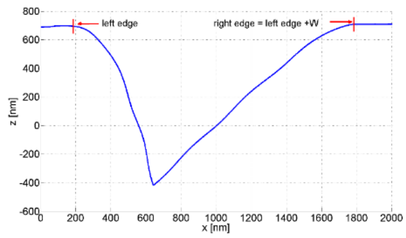


Figure 6 Search the edges of the rectangular structure with the gradient range method

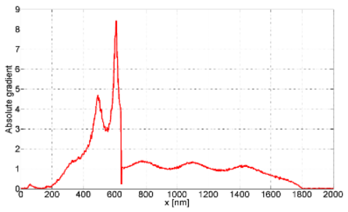
If the width of the groove is known, then the structure width method can be used to search the edges of the rectangular structures (see Fig. 9). After levelling on the ridge top, the ridge top becomes flat. The absolute values of the gradients on the ridge top are smaller than those at the edge and groove. With the known condition of the width W of the groove, a profile segment of length W with maximal sum of the absolute values of the gradients is searched.



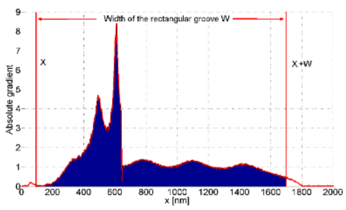
(a) Measured profile of a rectangular groove after 1st order levelling on the ridge top profile segment.



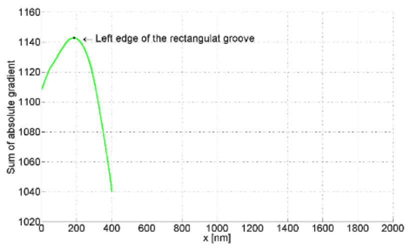
(e) The right edge of the rectangular structure is the distance of the groove width W from the left edge.



(b) The absolute values of the gradient of the profile $|gr(x)|$.



(c) The sum of absolute values of the gradients from x to x+W $GR(x) = \sum_x^{x+w} |gr(x)|$.



(d) The position with maximal GR(x) is the left edge of the rectangular groove.

Figure 7 Search the edges of the rectangular structure with the structure width method.

For an accurate tip form characterization, the structure width method demands the exact information of the rectangular structure width, and the traverse direction should be perpendicular to the structure. The uncertainty of the structure width affects the characterized tip width directly. The advantage of the structure width method lies in that it has no limit on the characterized tip form. It can characterize not only sharp tips, but also blunt or even flat tips. In investigating the tip abrasion through characterizing the abrased tip with time, the structure width method offers a better stability than the gradient range method.

The gradient range method demands no extra information on the characterizer rectangular structures. The criterion of top surface gradient distribution range *Δgr* influents the tip characterization accuracy. The gradient range method is only for relatively sharp tips, not for very blunt or flat tips.

2.2 Razor blade standard

A razor blade standard is a wedge shape standard with a sharp knife edge (see Fig. 10). The sharp knife edge characterizes the tip radius. If the wedge side is steep enough, it can also characterize the opening angle of the tip.

The imaging procedure of the razor blade standard is shown in Fig. 11. The dashed line is the trace of the tip apex, and the tip form at different positions is shown with dotted lines. The advantage of the razor blade standard lies in that the measured profile is the outline of reconstructed tip form and no extra procedures are necessary. In Fig. 12 the reconstructed tip form (the reverse of the imaged profile, dashed line) is compared with the real tip form (dotted line).

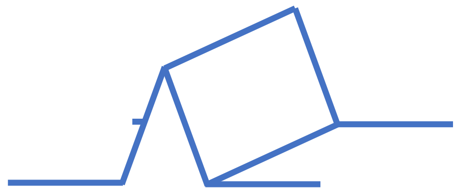


Figure 8 Razor blade standard

The rectangular standard can characterize both the tip radius and the opening angle, but the uncertainty of the tip radius characterization depends on the accuracy of the rectangular structure edge positions determination. Compared to the rectangular standard, the razor blade standard can characterize the tip apex and tip radius precisely because of the sharp knife edge. The inclination of the tip outline can also be characterized if the razor blade standard is steeper than the tip (see right tip outline in Fig. 12). In the opposite case, the reconstructed tip is wider than the real tip, as the left reconstructed tip outline shown in Fig. 12.

The diamond knife from DiATOME (see Fig. 13) [4, 5] can be used as a razor blade standard. The opening angle of the cutting edge is 45°, and the radius is about 5 nm.

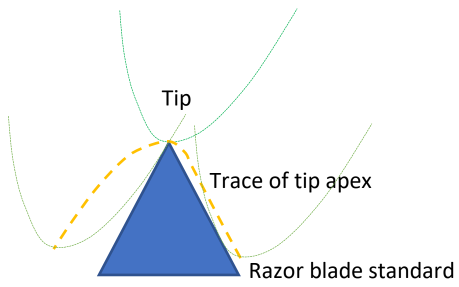


Figure 9 Imaging the razor blade standard.

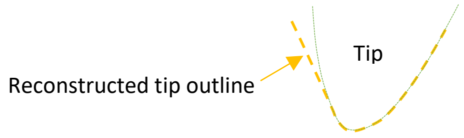


Figure 10 Comparison of the reconstructed tip outline and the real tip form.

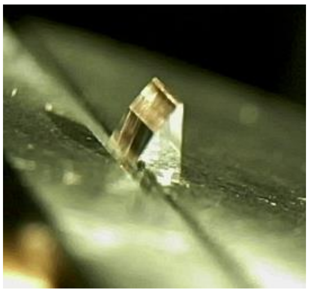


Figure 11 Diamond knife with the opening angle of 45° and tip radius of about 5 nm.

2.3 Wedge 2D-radius standard

A wedge 2D-radius standard is a wedge shape standard with round edge (see Fig. 14). The radius *R* of the round edge is much larger than that of the sharp knife edge of the razor blade standard and has already been calibrated. The round edge with µm radius makes the measurements easier and friendly to the tip, compared to the knife edge.

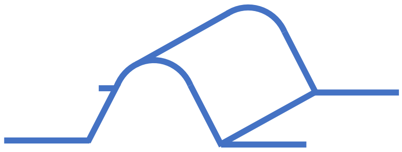


Figure 12 Wedge 2D-radius standard

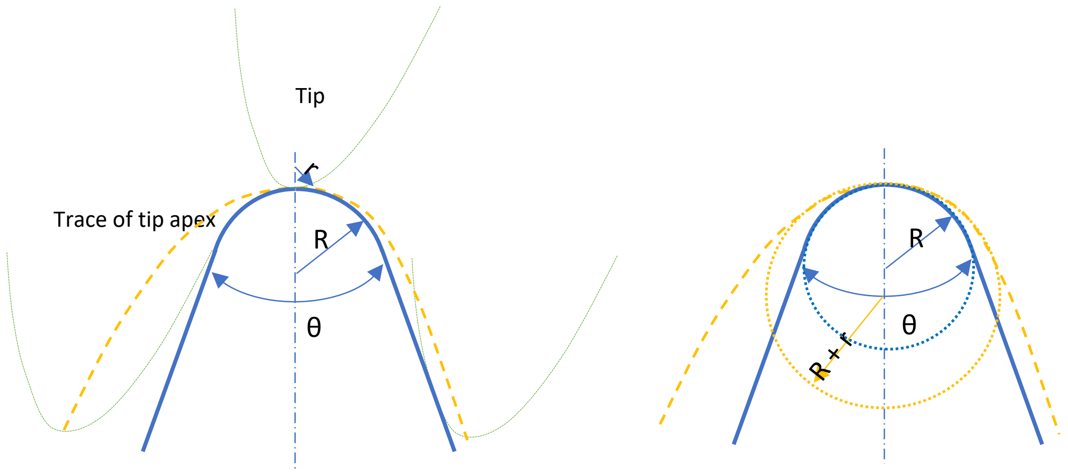
Fig. 15(a) shows the imaging procedure of the wedge 2D-radius standard. The dashed line is the trace of the tip apex, and the tip form at different positions is shown with dotted lines. The tip radius *r* is the difference between the evaluated profile radius and the given round edge radius *R*, as shown in Fig. 15(b). If the side inclinations of the wedge 2D-radius standard are steeper than those of the tip outline, the opening angle of the tip can also be characterized.

HALLE GMBH produces a wedge 2D-radius standard with radius R = 1 µm and opening angles of 70°, 90° and 120°.

It should be noted that only the data points within the measuring depth are used in tip radius evaluation. The measuring depth *t* (see Fig. 16) is the depth of the round surface on the wedge 2D-radius standard. The measuring depth is determined by the round edge radius *R* and the opening angle g of the wedge

$$t = R - R * \sin\left(\frac{g}{2}\right) \quad (2)$$

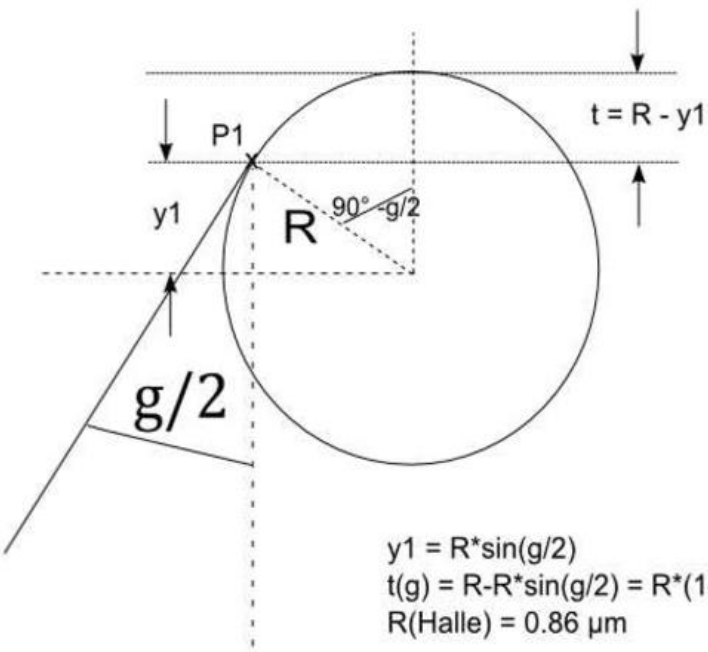
For a determined round edge radius *R,* the larger the opening angle *g*, the smaller the measuring depth, and the more difficult to get an accurate radius through circle fitting.



(a) The imaging procedure of a wedge 2D-radius standard

(b) The tip radius *r* is the difference between the evaluated profile radius and the given round edge radius *R*.

Figure 13 The imaging procedure of a wedge 2D-radius standard



y1 = R*sin(g/2)
t(g) = R-R*sin(g/2) = R*(1-sin(g/2))
R(Halle) = 0.86 µm

g	g/2	sin(g/2)	t(g)
120 °:	60 °	0.866	0.115 µm
90 °	45 °	0.707	0.252 µm
70 °	35 °	0.574	0.367 µm

Figure 14 The measuring depth that is used to perform circle fitting and evaluate the tip radius, courtesy of HALLE GMBH.

Table 1 Comparison of tip characterizers

Name	Uses	Properties
2D rectangular standard	Characterization of ☒ Tip radius ☒ Opening angle	+ Can characterize all parameters - The accuracy of rectangular edge position determination affects the characterization uncertainties - Sharp knife edge brings difficulty to measurements
Razor blade standard	Characterization of ☒ Tip radius ☒ Opening angle	+ Measured profile is the outline of reconstructed tip - Sharp knife edge brings difficulty to measurements
Wedge 2D-radius standard	Characterization of ☒ Tip radius ☒ Opening angle	+ Round end makes the measurement easier than the knife edges - The calibration uncertainty of the round end brings extra characterization uncertainty

☒ Capable ☒ Possible ☐ Unable

3. Summary

This good practice guide introduces 2D tip form characterization methods with three different tip characterizers. The uses and properties of these tip characterizers are listed compared in Table 1.

If accurate tip radius characterization is demanded and no other parameter is demanded, the razor blade characterizer is a good choice. If not only tip radius, but also the opening angle should be characterized, such as the tip for indentation, then the 2D rectangular standard meets the demand. If the tip is fragile, the wedge 2D-radius standard is more friendly to the tip.

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