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MEASUREMENTS OF STYLUS RADII*

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Summary

In stylus measurements of surface texture the measured results for roughness depend on the stylus radius. Therefore it is important to determine the stylus radius. Since stylus tips are not perfectly spherical, the local radius of curvature varies significantly over the surface which makes the determination of an effective radius difficult. Both the techniques used to generate stylus profiles and the subsequent algorithms used to derive an effective radius are discussed. Comparisons are made between three techniques: sharp-edge traces, optical microscopy and scanning electron microscopy. Several algorithms, including that prescribed by the American National Standard ANSI B46-1, are discussed. It is concluded that the radius scale method is accurate, unambiguous and easy to use for routine measurements in the laboratory.

1. Introduction

Several methods for measuring the radii of styli used in surface texture instruments are compared. Knowledge of the stylus radius is important for several reasons. First the sharpness of the stylus partially determines the maximum force with which a stylus may bear on the surface without damaging it. Second the horizontal resolution or the ability of the instrument to resolve various surface features depends on the stylus radius. This consideration is important when using the stylus technique to study optical surfaces whose quality may depend on surface features separated by distances as small as an optical wavelength (about 0.5 μm for visible light). The standard 10 μm stylus may be totally unsuitable for this application. Third the measured result of the average roughness R_a of manufactured surfaces is a strong function of the stylus radius [1]. Finally the calibration of surface roughness instruments by the use of precision reference specimens

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depends on the stylus radius (ref. 2, p. 14). It is therefore important that the experimental methods and algorithms for determining stylus radii be standardized.

Several techniques of stylus measurement were studied to find the one best suited for routine quality checking in the laboratory and to establish a basis for standardizing stylus radius measurements. This investigation is an outgrowth of work done as part of the ANSI B46.1 Special Subcommittee for investigating stylus tip measurements. Two aspects of the problem are discussed: (1) obtaining a profile of the stylus tip and (2) defining the algorithm for obtaining the radius from the profile. The latter problem is rather tricky because stylus tips are not perfectly spherical and the local radius of curvature varies from place to place. In Section 2 the methods for obtaining the profile are discussed. Section 3 deals with some of the algorithms used for defining a radius. Section 4 contains the results obtained with the various methods and algorithms together with conclusions concerning a reasonable approach to the problem.

2. Methods of imaging

This discussion is limited to methods of imaging the two-dimensional profile or silhouette of the stylus tip. Although the horizontal resolution of surface texture measurements is in general related to the overall three-dimensional structure of the stylus tip this overall structure is easily inferred from several two-dimensional images of the tip profile. Therefore the three-dimensional problem can be reduced to a two-dimensional one. All profiles shown were made in the direction of travel of the stylus.

The three techniques used for taking an image of a 1 - 10 μm radius stylus are scanning electron microscopy (SEM), optical microscopy and sharp-edge traces using the stylus itself.

2.1. Scanning electron microscopy

SEM is an important technique for examining styli [3 - 7]. In general the image of the specimen area being examined is formed on a cathode-ray tube from the current of secondary electrons emitted when the area is bombarded by a high energy well-focused electron beam. Since the resolution is routinely better than 0.05 μm very small features can be resolved on the surface of an object. The depth of field is large so it is easy to image the profile of a stylus tip. Therefore by using the SEM the true geometrical profile of the stylus is obtained with very high resolution. SEM micrographs of four different styli are shown in Figs. 1(a), 2(a), 3(a) and 4(a). All had a pyramidal shape with an apex angle of 90°. The micrographs, which were taken with an incident beam energy of 20 kV, clearly show that stylus tips can have highly irregular profiles. Figure 1(a) shows a fine stylus whose radius is approximately 1 μm. This stylus tip is the most nearly spherical of

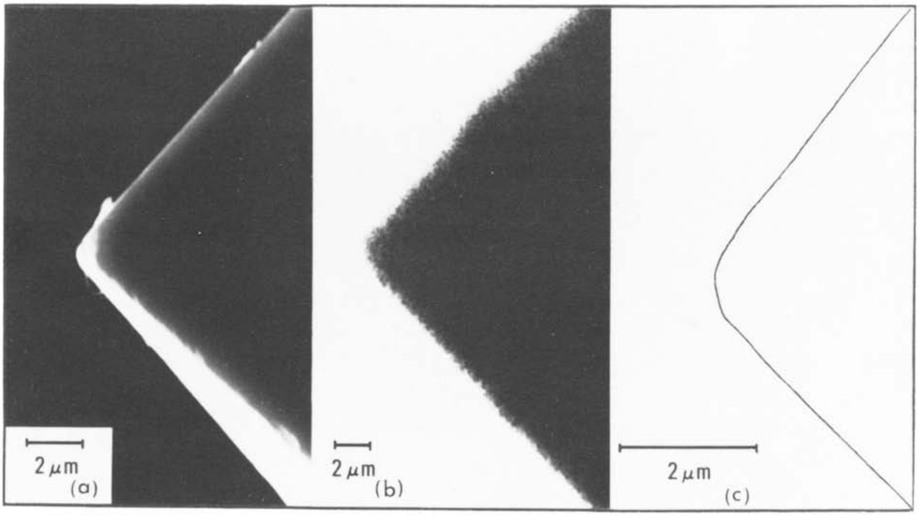


Fig. 1. Magnified profiles of a fine stylus used in the measurement of surface texture: (a) SEM micrograph, (b) optical micrograph; (c) razor-blade trace.

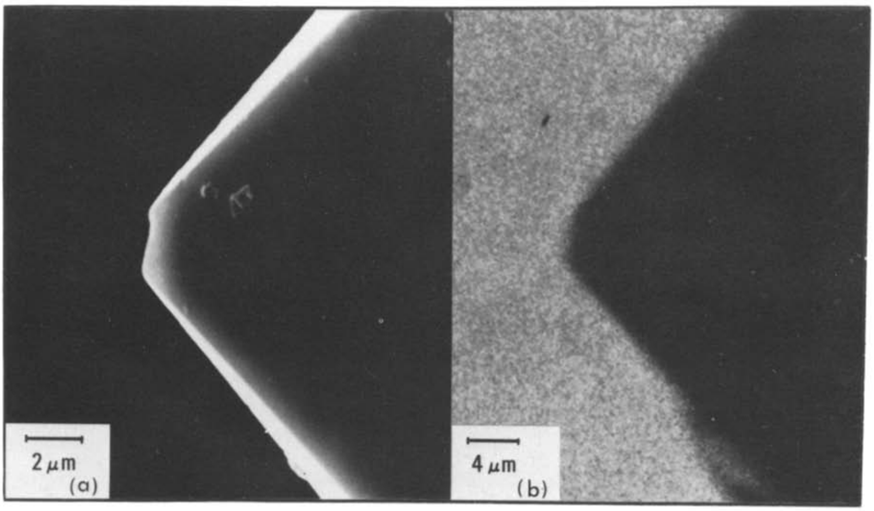


Fig. 2. Magnified profiles of a nominal 10 μm stylus: (a) SEM micrograph; (b) optical micrograph.

the four. In contrast, Fig. 2(a) shows a new unused stylus which is supposed to have a radius of 10 μm in accordance with the American National Standard B46.1-1978 [8]. The width of the tip is only about 2 μm and the radius is almost impossible to define owing to the jagged structure. Therefore the SEM is useful for quality control of styli of this nature. Figure 3(a) shows a stylus which has been in regular use in the laboratory for about eight years. It was originally rated as having a radius of 2.5 μm but measurements indicate that the present radius is about 7.5 μm. This difference may be due

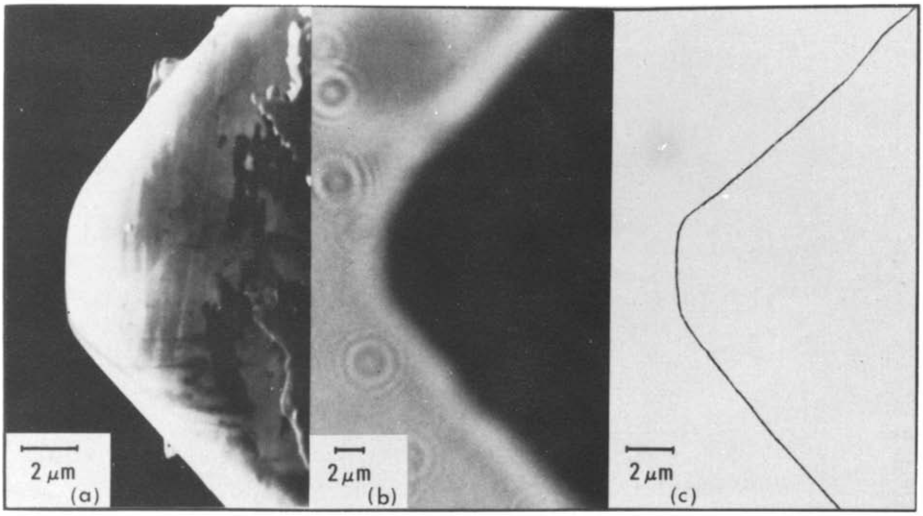


Fig. 3. Magnified profiles of a nominal 2.5 μm stylus: (a) SEM micrograph; (b) optical micrograph; (c) razor-blade trace.

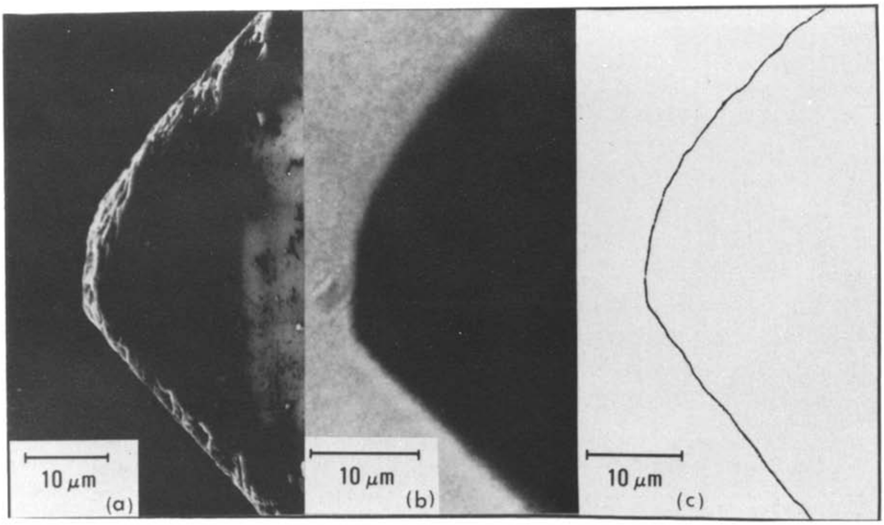


Fig. 4. Magnified profiles of a nominal 12.5 μm stylus: (a) SEM micrograph; (b) optical micrograph; (c) razor-blade trace.

to wear which may have taken place during the early stages of use; however, measurements indicate that the shape of the tip has changed very little in its last four years of operation. Figure 4(a) shows a stylus with a nominal radius of 12.5 μm. This is interesting because the local radius of curvature changes smoothly from place to place and because it is highly asymmetrical.

In all four cases the SEM gives an accurate highly resolved image of the tip profile whose radius can be easily measured once an appropriate algorithm has been decided.

There are two precautions which must be observed when using the SEM. First the diamond styli should be coated with a conducting film in order to ensure against distortion of the image due to charging of the insulating diamond surface. To obtain Figs. 1(a), 2(a) and 3(a) a Pd–Au alloy was sputter coated on the specimen to a thickness of about 75 - 100 Å before insertion in the SEM. Figure 4(a), however, was obtained without the conducting film. For reasons not yet known the coating process seems to be unnecessary for styli with larger radii. Second the magnification of the images must be calibrated since it may vary by 20% from one pumpdown to the next. In the present work the calibration was done using a calibrated line spacing specimen developed by Ballard [9] and marketed by the National Bureau of Standards as a standard reference material (SRM). The stylus and calibration scale were mounted simultaneously in a rotary sample holder. During operation the line scale was first rotated into the SEM beam to produce an image of a calibrated line spacing so the magnification could be determined. Then the stylus was rotated into the beam to produce a stylus image at the calibrated magnification. Finally an important drawback of SEM is that the stylus must be removed from the surface instrument in order to take the SEM profile.

2.2. Optical microscopy

Optical microscopy is an alternative technique to SEM for obtaining the direct profile of a stylus tip. The resolution is poorer, however, and any structure on the scale of a micrometer is likely to be lost by diffraction. One important limitation is the geometry of the stylus itself. High resolution is achieved by using an objective lens with high numerical aperture (NA). However, a long working distance between the stylus tip and the objective lens is required so that there is clearance between the lens and the stylus shank. In the present investigation the shank diameter was about 1.5 mm. Therefore the working distance had to be at least 0.75 mm. The long working distance together with other limitations on the size of the lens resulted in a small NA of 0.25 for which the theoretical resolution is about 2 μm.

Optical micrographs of the four styli already discussed are shown in Figs. 1(b), 2(b), 3(b) and 4(b). The microscope was operated in the bright field transmittance mode with green light (λ = 0.546 μm). Kohler illumination was used for all but the 2.5 μm stylus (Fig. 3(b)). The limited resolution is shown best for the 10 μm stylus in Fig. 2(b) where the optical micrograph reveals only a trace of the jagged feature shown in Fig. 2(a). Although it seems possible to measure a stylus radius of 10 μm with a technique which has 2 μm resolution, features at the level of 2 μm which could strongly influence a profile radius measurement are nevertheless unresolved by this technique. Thus optical microscopy should not be used for quality control of styli with radii less than 10 μm. For larger objects, however, the optical micrograph is of some value. The asymmetry in the 12.5 μm stylus is shown clearly by the optical micrograph in Fig. 4(b).

2.3. Sharp edge traces

In this procedure the stylus is traversed at a very slow speed over an edge with a radius of curvature much less than that of the stylus tip [10] and the resulting profile is recorded on an xy recorder. The use of a razor blade for this purpose was first discussed by Teague [11]. The blade has a radius of about 0.1 μm and a very steep flank (about 80° as compared with the 30° - 45° flanks of the styli themselves). Therefore as long as the stylus radius is 1 μm or more the output signal from the pick-up gives an accurate profile of the stylus as it passes over the blade. Some sample traces are shown in Figs. 1(c), 3(c) and 4(c). The highly irregular stylus of Fig. 2 was not installed in the stylus instrument and the sharp-edge approach was not used. Comparison of these traces with the corresponding SEM profiles demonstrates that there is very little elastic deformation of the razor blade edge. It seems clear that this method yields an accurate profile even for the fine stylus at a magnification of 31 000X. The stylus force for these traces was approximately 5×10^{-4} N.

This technique is relatively inexpensive as it requires only the stylus instrument which gives the profile output and an xy recorder. It is also an advantage that the procedure is carried out while the stylus is installed in the instrument. However, there are other aspects of this procedure that require care. The speed of the traverse is limited by the response of the recorder. Therefore the traverse must be as slow as 0.001 - 0.01 mm s^{-1} so that the tip profile can be recorded in a reasonably long time, say 1 - 2 s. At the same time, for simplicity, there should not be any distortion of the output profile due to a difference between the vertical and horizontal magnification of the recorder otherwise processing of the signal is required to compensate for the distortion. Therefore the recorder gain must be continuously adjustable so that the horizontal magnification can be made equal to the vertical magnification. The magnification can be measured by taking profiles of well-characterized step-height and wavelength artifacts. If the apex angle of the tip is already known, a quick technique for producing an undistorted profile is to adjust the relative x and y gains so that the apex angle of the recorded profile is equal to the apex angle of the tip.

Another important consideration is guarding against bending of the blade under the force of the stylus. The blade tends to bend away from the stylus first one way and then the other as the stylus passes over the blade. This bending, which would result in a decrease in the apparent radius of the stylus tip, can be minimized by clamping the blade as close to the edge as possible. In the case of the fine stylus (Fig. 1(c)) the blade was clamped 0.4 mm below the top edge. The absence of discontinuities in the resulting profile suggests that there was negligible distortion due to razor bending. The profile, which was recorded at a magnification of 31 000X, also required an extremely slow scanning speed. This was accomplished by traversing the blade rather than the stylus. The slow motion was generated with a piezo-driven scanning stage developed by Scire and Teague [12]. If computerized data acquisition were used instead of an xy recorder the speed would only be limited by the dynamic response of the stylus instrument itself.

3. Algorithms for determining a radius

This section is principally concerned with algorithms for directly measuring the effective radii of stylus tip profiles. If the image of a stylus tip were a perfect arc of a circle, determining the radius would be straightforward. However, since many styli tend to have flat tops the radius of curvature varies over the surface and the problem of drawing the best circle becomes highly ambiguous. A good algorithm must therefore be capable of deducing an effective radius from stylus profiles which may have non-ideal shapes. In addition the effective radius must be related to the function of the stylus as a surface-measuring instrument.

In order to determine a radius one must first determine where to place the center of the circle, what fraction of the circle should be fitted to the stylus tip, and conversely what fraction of the arc of the stylus tip should be fitted to the circle. These problems cannot be solved straightforwardly with a computer. The fit involves a non-linear regression in three parameters and the length of arc to be fitted is quite ambiguous, *i.e.* a tiny circle may fit a tiny section of the stylus arc better than a large circle will fit a larger section of arc.

Several algorithms have been considered including the approach recommended in the American National Standard ANSI B46.1-1978 [8] and the technique known as the radius scale method was found to be the best.

3.1. ANSI Standard approach

The ANSI Standard recommends the following procedure for determining the effective radius of a stylus tip [8]: "Effective radius here is defined as the average of the two concentric and minimally separated radii, whose center falls on the conical flank angle bisector, whose arcs are limited by lines drawn 30° either side of this bisector, and which contain between these radii the stylus tip profile."

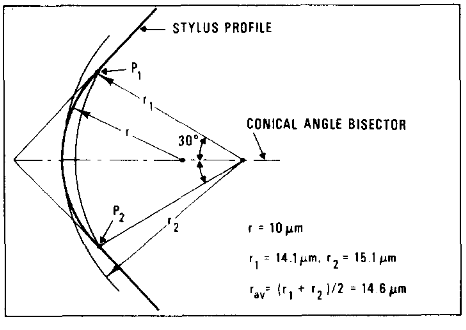
This appears to be the first attempt by any national standards committee to state a radius measurement procedure explicitly. As such it is under active investigation and re-evaluation by the committee. Although the procedure is adequate for measuring some stylus profile shapes it does not explicitly state how to choose the end points of the stylus tip profile and it can therefore lead to ambiguity.

The problem is illustrated in Fig. 5 where the procedure is used to fit an ideal stylus shape with a 90° apex angle and a radius of 10 μm. It would seem that the two concentric circles and the ±30° angle should contain the entire end profile between the points P_1 and P_2 where it joins the straight flanks of the stylus. The center of the circles is then determined by the intersection of the ±30° lines with the bisector. However, this procedure yields a radius of 14.6 μm when in fact the stylus tip was drawn as a perfect circle with a radius of 10 μm. Therefore as interpreted for the beginning and end points P_1 and P_2 the procedure in the ANSI Standard gives the incorrect radius for perfectly constructed styli. It can be rectified by using ±45° angles instead of ±30° when the stylus apex angle is 90° and ±60° angles when the stylus apex angle is 60°, and by using the above interpretation for the end points. The four styli depicted in Figs. 1 - 4 all have 90° apex angles. Therefore ±45° angles were used to determine the center of the circles and hence to derive effective radii for the four styli. The results are discussed in Section 4.

One disadvantage of the modified algorithm is the difficulty of locating the end points of the stylus arc, *i.e.* determining where the curving profile of the tip begins and ends. Another disadvantage is that sections of the stylus tip near the flank are fitted to a radius but they would never contact the surface during roughness measurements. Surfaces are rather smooth in the wavelength regime from 1 to 100 μm and it is rare when the slope is as large as 15°. Therefore a new method has been devised which measures the radius of only the endmost 30° of the stylus arc and which avoids some of the ambiguity of the ANSI Standard approach.

3.2. *Radius scale method*

In this method the stylus profile is fitted to a transparent radius scale whose pattern is shown in Fig. 6. The scale consists of a series of concentric arcs with different radii which span an angle of 30°. The scale is simply placed over the stylus image and the end profile is matched to one of the arcs. It is usually necessary to begin with some guideline concerning the minimum length of arc of the stylus to use. This is done by first inscribing the profile in a 150° angle as shown at the left of the radius scale. The bisector of this angle is held parallel to the bisector of the apex angle and the scale is positioned so that the stylus is inscribed in the 150° arc. The two points of contact are defined to be the end points of the stylus arc. One then begins the fitting procedure by matching the stylus arc with the circular arc whose end points match those of the stylus arc. If the stylus arc appears to be too flat (the opposite has never been encountered) larger circular arcs are



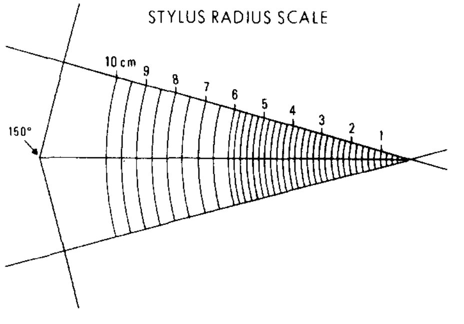


Fig. 5. Diagram showing the procedure for measuring the radius of a stylus according to the ANSI Standard B46.1-1978. The true radius is 10 μm but the measured value is 14.6 μm. P_1 and P_2 represent the points where the arc of the tip meets the straight flank of the stylus.

Fig. 6. Diagram of radius scale used for measuring the radii of magnified stylus profiles.

chosen until one is found which best matches the stylus profile over the entire 30° circular arc.

This method seems to be unambiguous although the fitting is accomplished by eye. One disadvantage is that visual fitting is difficult unless the radius of the magnified image is at least 1 cm. Therefore the magnification of the final image must be high.

3.3. Precision reference specimen method

As a check on the two direct algorithms the commonly used approach of determining the effective radius by measuring the apparent average roughness R_a of a calibrated precision reference specimen (PRS) with each stylus has been applied. The specimen has a triangular profile with an included angle of 150°. The nominal R_a is 0.5 μm. For a simple profile like this it is possible to calculate how the measured R_a will decrease with increasing stylus radius. If the true average roughness R_{a0} of the PRS is known then an effective stylus radius can be calculated for each stylus from the measured R_a by using the correction chart in the ANSI Standard B46.1-1962 (ref. 2, pp. 22 - 23). In the present work R_{a0} was calculated by assuming that the fine stylus had a radius of 0.92 μm as measured by the other methods and by applying the appropriate correction to the value of R_a measured with this stylus. Effective values of the stylus radius for the nominal 2.5 μm and 12.5 μm styli were determined from the measured R_as for each.

The main disadvantage of this approach is that its accuracy depends on the accuracy of the mathematical profile which is used to represent the surface profile. Another difficulty is that the R_a results are fairly insensitive to the stylus radius for small radii.

4. Results and conclusions

Table 1 shows the results of radius measurements of the four styli using the three imaging techniques and the three algorithms for defining the radius. In general the quoted uncertainties are equal to the random error of one standard deviation which is by far the largest component of error. This error arises from the difficulty and the variability associated with using either of the algorithms discussed in Section 3. For a small number of results there were insufficient data to calculate a standard deviation or else the standard deviation was smaller than appeared to be reasonable. In these cases the random error was determined from estimates of reasonable upper and lower bounds for the measured values. It appears that the variability of the ANSI Standard approach is significantly greater than that of the radius scale method. Therefore the latter method is to be preferred. The major difficulty associated with the former method is the difficulty of determining the end points of the tip profile, *i.e.* the points where the arc of the tip meets the straight flank. In the case of the 2.5 μm stylus the ANSI Standard approach gives one result (2.7 ± 0.3) which completely disagrees with all others.

TABLE 1

Summary of results of stylus radius measurements

Technique	Stylus			
	Fine	2.5 μm	10 μm	12.5 μm
SEM				
r_{RSM} (μm)	0.8 ± 0.1	8.1 ± 0.5	6.6 ± 0.4	22.6 ± 2.5
r_{ST} (μm)	0.8 ± 0.1	5.6 ± 0.6	1.4 ± 0.2	21.7 ± 2.2
Optical				
r_{RSM} (μm)	⩽2.1	6.0 ± 1.2	5.9 ± 2.1	21.3 ± 1.6
r_{ST} (μm)	1.2 ± 0.1	5.9 ± 1.9	3.3 ± 0.3	16.5 ± 3.1
Razor blade				
r_{RSM} (μm)	1.0 ± 0.1	7.0 ± 0.4	—	17.8 ± 3.4
r_{ST} (μm)	1.1 ± 0.1	2.7 ± 0.3	—	21 ± 13
PRS				
r_{PRS} (μm)	0.92 ± 0.16 (assumed)	6.9 ± 0.9	—	20.3 ± 1.8

r_{RSM} represents the results of the radius scale method. r_{ST} represents the results found by applying a modified version of the algorithm discussed in the ANSI Standard. r_{PRS} are results obtained indirectly from measured roughness averages of PRS taken with the different styli.

The results also show that the razor blade technique is an accurate method for generating a stylus profile. The measurements of r_{RSM} with the razor blade technique agree nicely with those measured by SEM. As a check on the direct methods the PRS results agree with the results obtained by the radius scale method applied to the SEM and razor blade profiles of the styli.

The quoted uncertainties for the PRS results are estimates of the 68% confidence intervals. They result from the uncertainty of the assumed radius of the fine stylus and the uncertainties of the R_a measurements of the PRS with the 2.5 and 12.5 μm styli.

In summary styli used in surface texture measurements can have some very irregular shapes and the actual radii may be different from the nominal values. The best techniques for measuring the radius and checking the stylus shape are razor-blade traces and SEM; however, optical microscopy may be sufficient for styli with radii greater than 10 μm. Once the stylus profile has been taken the analysis is straightforward and fairly unambiguous with the radius scale method. However, this technique is difficult unless the radius of the magnified image is greater than 1 cm.

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