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RANDOM PROFILE PRECISION ROUGHNESS CALIBRATION SPECIMENS

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Abstract

The design, specifications, testing, and potential use of random profile precision roughness calibration specimens are described. These specimens have measuring areas with unidirectional random profiles ($R_a = 0.10$–$0.012\,\mu m$) between two smooth reference surfaces. They were designed primarily to provide an overall means of checking for the readings of stylus instruments in their high-magnification range. However, the unique properties of the new specimens also make them very useful in establishing connections between the measuring results for roughness parameters and profile graphs, and the properties of the stylus instruments used to make the measurements.

Introduction

During recent years, great efforts have been concentrated on the measurement of smooth surfaces with $R_a \leqslant 0.1\,\mu m$. This roughness range plays an increasingly important role in both scientific research and the industrial area. There are many kinds of instruments, including many kinds of stylus instruments, that could be used for this purpose. There are likewise many surface parameters that could be selected for quantifying the properties of smooth surfaces, as well as many factors which could affect the correctness of smooth surface measurement. Therefore, a salient question with which researchers are always faced is: when two different types of profiling instruments measure the same surface (or even one instrument operating under two different measuring conditions), do they get the same results, and if not, why not?[1]

It was almost impossible to answer this question until we made a precise definition of what the "same surface" is and how to make a replica of it.

In 1965 J. Hasing at PTB produced his random profile roughness calibration specimens,[2] which partly provided a means in the range of $R_a = 1.5$–$0.15\,\mu m$ to answer this question. These specimens have a measuring area of random profiles (obtained by grinding) in the direction of traverse, and the random profiles repeat every 4 mm, a distance equal to the traversing length. Each of the profiles could be regarded as a "random profile unit". Normal to the measuring direction of the specimen, however, the surfaces are flat, so the profiles maintain a constant form. During the measuring process, the stylus will always measure exactly the same "random profile unit" (with various phases), irrespective of the measuring position. Theoretically, the values of roughness parameters will always keep constant for every measurement. Therefore, any part of the measuring area of PTB specimens could be regarded as the "same surface" as any other part, for constant information of the "random profile unit" is contained by PTB specimens.

PTB specimens have been accepted by ISO as ISO/5436–1985 specimens type D.[4] As a kind of standard reference material for overall checking of the readings of stylus instruments, PTB specimens and their replicas have been widely used both in scientific research and in the industrial area. Their properties are shown on the left side of Table 1.

Design

Two decades have passed since J. Hasing made his excellent specimens available and many successes in surface metrology have been achieved with them. Today, however, many stylus instruments for measuring smooth surfaces should be checked for readings in their high-magnification range before using them. Researchers always want to make intercomparisons of their measuring results, not only of surface roughness parameters but also of profile graphs and topographies. These may be obtained from various measuring methods or from instruments under different measuring conditions (such as stylus radius, stylus load, filter, skid, traversing speed and digitization). Ideally, intercomparisons of different methods and instrumental conditions should be performed with the "same surface".

From the above point of view, specimens type D in ISO/5436–1985 have

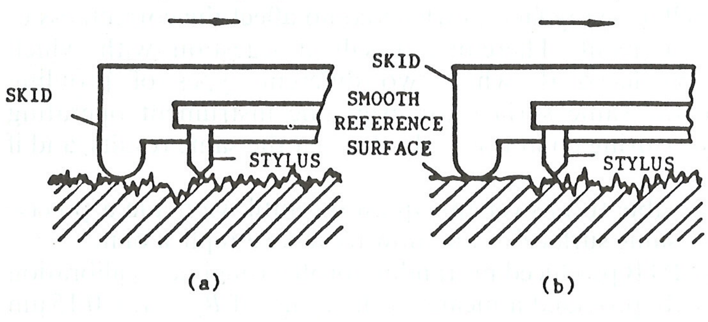

Figure 1 *Two designs for supporting surface of the skid. (a) PTB specimens (ISO/5436–1985, type D); (b) CIMM specimens.*

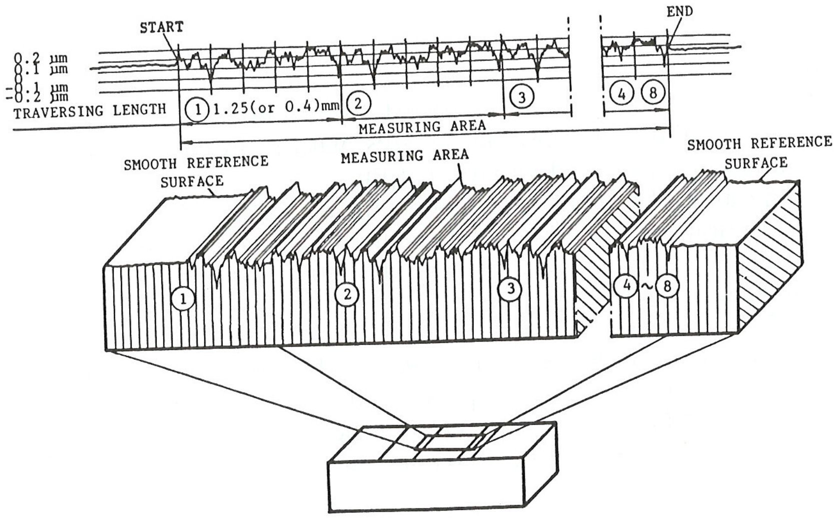

Figure 2 *Random profile precision roughness calibration specimen.*

some shortcomings: (1) The R_a values were 1.5, 0.5 and 0.15 (or 0.2) µm, so the stylus instruments calibrated by specimens type D were limited so far as their range was concerned. (2) At both sides of the measuring area, there was not a smooth datum plane to make clear bounds at the start and end of the data: it was therefore inconvenient to make comparison among the profile graphs obtained from various measuring methods and instruments. (3) For specimens type D of ISO/5436–1985, the skid moved on the rough surface of the specimen (see Figure 1a), so a measuring error would result from the phase error between the skid and stylus (moving inphase or outphase).

To overcome these shortcomings of the type D specimens, some new precision roughness calibration specimens with random profile were designed (Figure 2), with R_a values of 0.10, 0.05, 0.025 and 0.012 µm and traversing length of 1.25 or 0.4 mm, so that stylus instruments could be calibrated in their high-magnification range.

The measuring area of the new specimens is composed of several (4–8) identical unidirectional random profiles. At both ends of the measuring area, however, there are two smooth reference surfaces located on (or parallel to) the mean lines of the random profiles of the measuring area (Figure 2). The borders formed between the smooth reference surfaces and the measuring area can be used as the start and end of the random profiles. Therefore, the specimens can be used to make calibrations and comparisons among measured parameters as well as the profile graphs. The smooth reference surface can also be used as the supporting surface for the skid (Figure 1b), so that the kinetic error of the skid can be reduced to a minimum.

Specifications

Measuring area
The measuring area of PTB specimens is about $8 \times 16\,mm^2$. It consists of four identical unidirectional random profile surfaces, with a profile repetition of 4 mm and R_a values of 1.5, 0.5 and 0.15 (or 0.2) μm.

The measuring area of CIMM specimens with R_a values of 0.1, 0.05 and 0.025 μm is also composed of four identical unidirectional random profile surfaces (see Figure 2), with a profile repetition (ie. traversing length) of 1.25 mm, so the length of the measuring area is 5 mm. The profile repetition length of the CIMM specimens with R_a value of 0.012 μm is only 0.4 mm (equal to the traversing length), and the measuring area as designed consists of six or eight identical unidirectional random profile surfaces and therefore has a length of 2.4 or 3.2 mm. Otherwise, the length of the measuring area might be too small ($0.4\,mm \times 4 = 1.6\,mm$) to be used conveniently.

Smooth reference surfaces
At each side of the measuring area a smooth reference surface is specified. The left one could be used as the supporting surface of the skid. Its length, about 5 mm, is sufficient, because the distance from the skid to the stylus is usually about 3–4 mm. The left intersected line can be also used as the start datum of the unidirectional random profiles. The right-hand smooth surface is used to provide only an end datum of the profiles, so its length is about 1 mm. Both of the smooth reference surfaces should be at the same vertical level, and should be situated on or parallel to the mean lines of the random profiles.

The smooth reference surfaces should have roughness $R_a \leqslant 0.008\,\mu m$, and flatness and coplanarity finer than 0.01 μm. For special applications, we can also provide specimens with higher-quality smooth reference surfaces of $R_a \leqslant 0.005\,\mu m$, and flatness and coplanarity finer than 0.008 μm.

Tolerances
The tolerances of the CIMM specimens are shown in Table 1.

The nominal values of R_a carry a large tolerance of 20–30% to permit economic fabrication, and the difference between the nominal value and the calibrated value is not regarded as an error. The standard deviation of R_a values from the mean value should not be more than 3–8%. This is the main quality index of the specimens. The standard deviation of the specimen with R_a value of 0.012 μm may be as large as 8%, because the "random profile unit" should appear six or eight times repeatedly in the 2.4 mm or 3.2 mm length of the measuring area. The fabrication as well as the measurement of this specimen is the most difficult among all the new specimens.

Uncertainty
The uncertainty (U) of the measurement of the stated mean value R_a depends both on the systematic error (Δ_c) of the instrument to be used and on the standard deviation (S) of R_a values of the specimen to be measured:[3]

$$U = \pm(\Delta_c + tS/\sqrt{n})$$

where t = coefficient of student "t" distribution. When $n = 12$ and $P = 95\%$, then $t = 2.179$, and

$$U = \pm(\Delta_c + 0.63S)$$

In order to determine the value of the systematic error of stylus instruments in their high-magnification range, a lot of theoretical and experimental work should be done. We measured our specimens with a Talysurf-6. Assuming that its systematic error Δ_c is 2–5% in the range of $R_a = 0.1$–$0.012\,\mu m$ and the standard deviation of R_a values of the specimens, S, is $\sim$ 3–8%, then an uncertainty value of $\pm$(4–10)% could be expected (see Table 1).

Hardness
The materials used should be hard enough to ensure adequate life and measuring accuracy. According to ISO/5436–1985, the materials should be harder than 750 Hv. However, PTB specimens have a rated hardness of HV $\geqslant$ 600.[3] We used a hardened steel having a specified hardness of more than 800 Hv, and testing results showed Hv $\geqslant$ 830. This is a very significant feature of the new specimens with R_a values of 0.1–0.012 µm. In fact, we often used the new specimens to check the random error of stylus instruments and after 25 repeated measurements over the same trace, no damage could be seen on the measuring area of the specimens with an optical microscope.

Testing and results

The identity of the profiles
The testing of the new specimens was in two stages. In the first, one unidirectional random profile surface was fabricated (Figure 3, left). In the second,

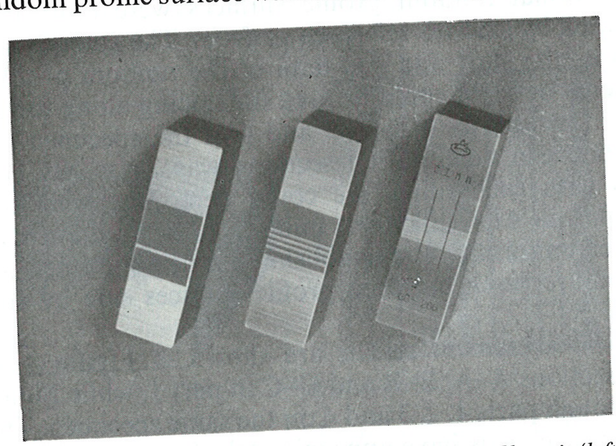

Figure 3 *CIMM specimens with one unidirectional random profile unit (left), and with several unidirectional random profile units, separated by smooth reference surfaces (middle), and side by side (right).*

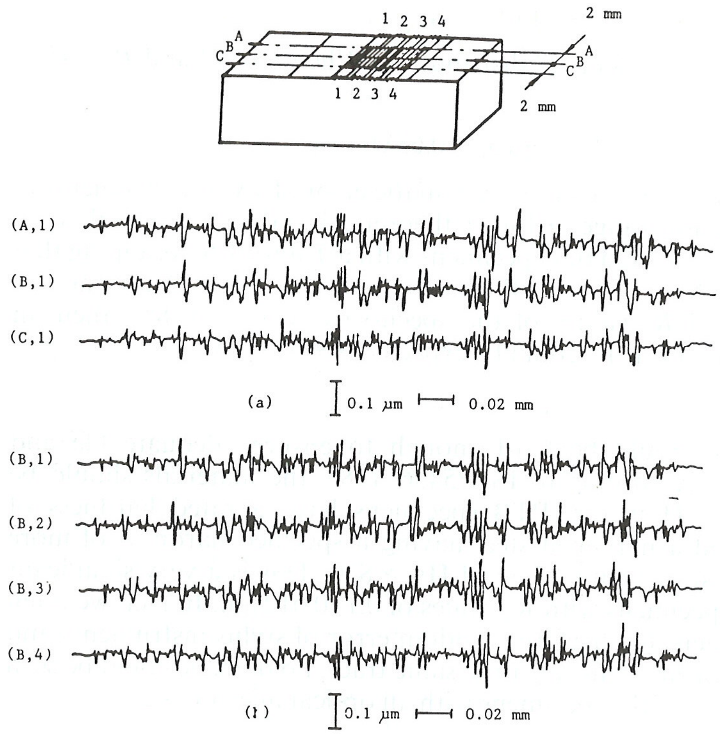

Figure 4 *The identity of the profile graphs. (a) Profile graphs from sections A–A, B–B and C–C in part 1 (Talysurf-4;* $V_v = 100{,}000\times$; $V_h = 500\times$; $r = 2.5\,\mu m$; *unfiltered; CIMM specimen no. 099). (b) From section B–B through parts 1, 2, 3 and 4 (Talysurf-4;* $V_v = 100{,}000\times$; $V_h = 500\times$; $r = 2.5\,\mu m$; *unfiltered; CIMM specimen no. 099).*

several unidirectional random profile surfaces were fabricated (Figure 3, middle), separated by smooth reference surfaces. The smooth–rough borders could be used as the start and end data of the random profiles. Therefore, stylus instruments or SEM could be used for tracing along the sections A–A, B–B and C–C through parts 1, 2, 3 and 4 of the specimen (see Figure 4). The distance between neighboring sections was 2 mm. By comparing the profile graphs with each other, we could determine whether or not the fabrication technique was sufficiently uniform to be used for making the new specimens. When uniformity was established the new specimen could be made with several unidirectional random profile surfaces side by side (Figure 3, right).

Some of the measurement results are shown in Figure 4. Figure 4a is recorded from sections A–A, B–B and C–C in part 1, while Figure 4b is from section B–B through parts 1, 2, 3 and 4 on the same specimen. The test results showed that the specimens have approximately constant profiles in both the crosswise and traversing directions. Therefore, the fabrication technique is considered to be sufficiently uniform.

In May 1987 we also tested the specimens with a three-dimensional surface topography system. This was a Talysurf-6 interfaced to an IBM/PC–XT at Shanghai Jiao Tong University by Professor Zhang E and Mr Lou Huazhou. The agreement could be seen between two sets of three-dimensional surface topographies and contour maps (see Figure 5a and 5b) obtained from different

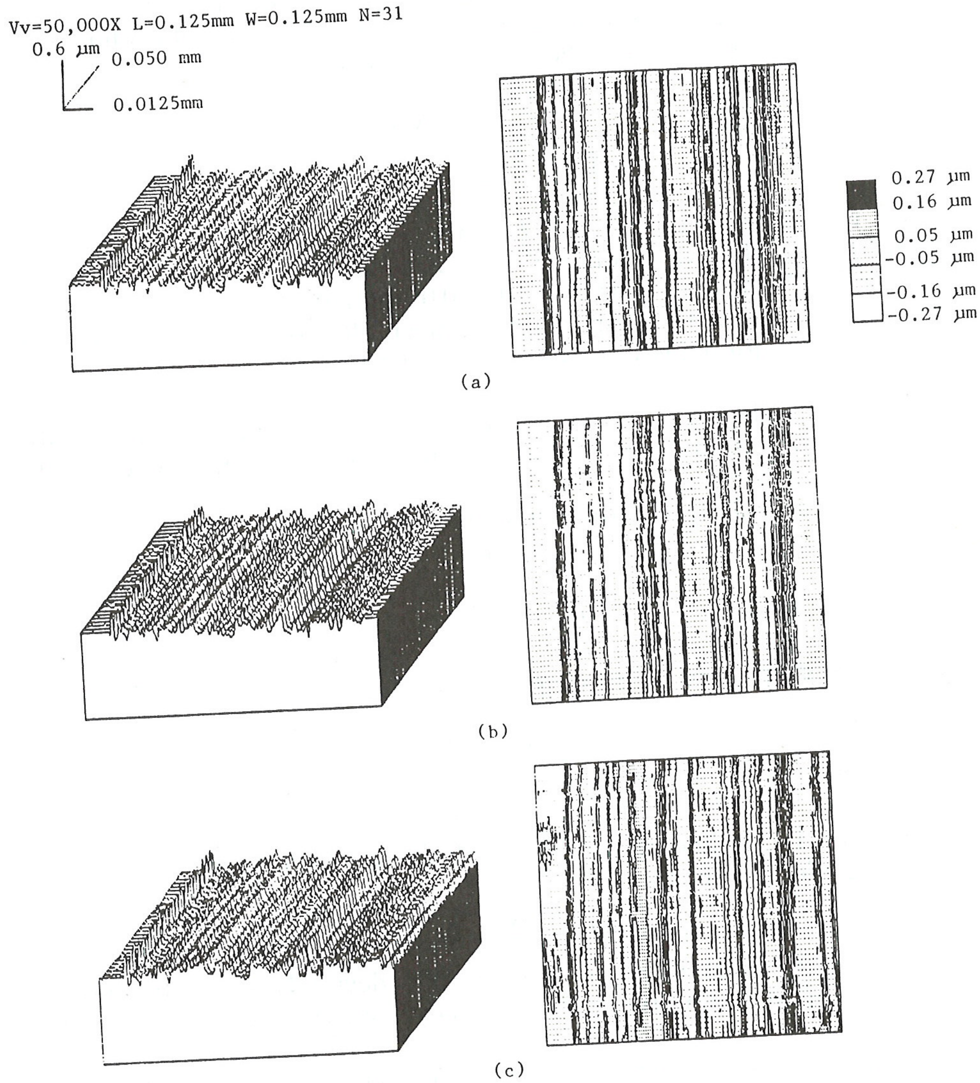

Figure 5 *Three-dimensional surface maps. (a) From part 1 of CIMM specimen no. 330, with the skid moving on the smooth reference surface. (b) From part 2 of CIMM specimen no. 330, with the skid moving on the smooth reference surface. (c) From part 1 of CIMM specimen no. 330, without skid.*

parts of one specimen respectively. In Figure 5, we can also see that the smooth reference surface is situated very close to the mean lines of the random profiles.

The identity of R_a *values*

The second stage of the testing of the new specimens involved the measurement of R_a values and consisted of two steps.

(1) First of all, the random error of the stylus instrument was estimated. By traversing a CIMM specimen 25 times precisely over the same track, or over several closely adjacent parallel tracks, the standard deviation of readings can be used as the random error of the stylus instrument:[4]

$$\sigma_c = \left\{\frac{\sum_{i=1}^{n} (R_a{}^i - \bar{R}_a)^2}{n-1}\right\}^{\frac{1}{2}}$$

Testing results showed that the random error of the stylus instrument Talysurf-6 at CIMM was about 0.7–1.3%, depending on the vertical magnification for CIMM specimens $R_a \approx 0.1$, 0.05 and 0.025 μm; $V_v = 20{,}000\times$, $50{,}000\times$, and $100{,}000\times$, respectively; and cutoff = 0.25 mm. The random error was 4.4% for CIMM specimen $R_a \approx 0.012$ μm, $V_v = 200{,}000\times$, and cutoff = 0.08 mm.

(2) The R_a values of the specimens was also measured at 12 evenly distributed positions in three (or four) sections at four (or three) different parts of the measuring area.

The mean value of R_a of 12 distributed readings is

$$\bar{R}_a{}^s = \frac{\sum_{i=1}^{n} R_a{}^i}{n}$$

The standard deviation of 12 readings is

$$\sigma_s = \left\{\frac{\sum_{i=1}^{n} (R_a{}^i - \bar{R}_a{}^s)^2}{n-1}\right\}^{\frac{1}{2}}$$

According to ISO standard 5436[4] the declared mean value (R_a) of the specimen should be given by

$$R_a = R_a{}^s - \Delta_c$$

where Δ_c is the systematic error of the calibrating device. However, because of the difficulty of estimating the Δ_c value exactly, we used the measured mean value $R_a{}^s$ instead.

The declared standard deviation of the specimen is[4]

$$\sigma = (\sigma_s{}^2 - \sigma_c{}^2)^{\frac{1}{2}}$$

The R_a mean value and standard deviation of the prototype specimens with $R_a = 0.10$, 0.05, 0.025, and 0.012 μm were also measured in various Chinese

Table 1 *Properties of PTB specimens (ISO/5436–1985, type D) and CIMM prototype specimens (1985)*

	PTB specimens (ISO/5436–1985) Type D	*CIMM prototype specimens (1985)*		
Property	*Specification of property*	*Specification of property*	*Measurement results*	*Pass*
R_a mean value (μm)	$1.5 \pm 15\%$	$0.10 \pm 20\%$	0.0928	Yes
	$0.5 \pm 20\%$	$0.05 \pm 25\%$	0.0561	Yes
	$0.15 \pm 30\%$	$0.025 \pm 30\%$	0.0274	Yes
		$0.012 \pm 30\%$	0.0154	Yes
Standard deviation of R_a	3% ($R_a = 1.5$)	3% ($R_a = 0.10$)	2.8%	Yes
	3% ($R_a = 0.5$)	4% ($R_a = 0.05$)	1.9%	Yes
	4% ($R_a = 0.15$)	6% ($R_a = 0.025$)	3.6%	Yes
		8% ($R_a = 0.012$)	6.5%	Yes
Uncertainty of measurement of R_a mean value	$\pm 3\%$ ($R_a = 1.5$)	$\pm 4\%$ ($R_a = 0.10$)		Unknown
	$\pm 3\%$ ($R_a = 0.5$)	$\pm 6\%$ ($R_a = 0.05$)		Unknown
	$\pm 5\%$ ($R_a = 0.15$)	$\pm 8\%$ ($R_a = 0.025$)		Unknown
		$\pm 10\%$ ($R_a = 0.012$)		Unknown
Smooth reference surfaces	None	$R_a \leqslant 0.008$ μm	$\leqslant 0.008$ μm	Yes
		Flatness $\leqslant 0.01$ μm	$\leqslant 0.01$ μm	Yes
Hardness	$H_V \geqslant 750$ (ISO)	$H_V \geqslant 800$	$\geqslant 830$	Yes
	$H_V \geqslant 600$ (PTB)			

laboratories. These were the National Institute of Metrology, Tsinghua University, Dongfang Institute of Measurement, and Changcheng Institute of Metrology and Measurement, using a Talysurf-4 interfaced to a computer, a Talysurf-5 and a Talysurf-6. The measured properties of the new specimens are shown in Table 1 on the right. However, owing to the difficulty of estimating the systematic error of the stylus instruments precisely, a major specification of the uncertainty of the R_a mean value still remained unknown. Although the maximum difference of measured R_a mean values among four laboratories was not more than 4.7%, and the uncertainty of measurement of the R_a mean value had been provided with a large tolerance ($\pm$4–10%), we are not sure that the error of the measurements fell within that tolerance, especially for the specimen with $R_a = 0.012$ μm. A more precise R_a mean value could be quoted if the effect of systematic error of the instrument could be considered and an intercomparison among some major laboratories in different countries could be performed.

With an improvement in our fabrication techniques, we have made the specimens recently with much less scatter both in R_a and in other parameters. Therefore the systematic error is the limiting error.

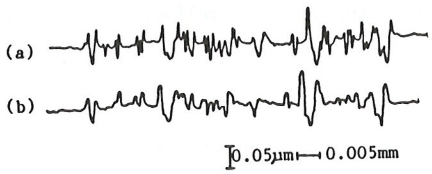

Figure 6 *The effect of stylus radius,* r. *(NBS Talystep;* $V_v = 200{,}000\times$*;* $V_h = 2{,}000\times$*; unfiltered; CIMM specimen no. 099; part 1; section B). (a)* r = *0.5 µm; (b)* r = *12.5 µm.*

Potential use

We intended primarily to use the new specimens for overall checking of the readings of stylus instruments in their high-magnification range. During the design, fabrication and testing of the new specimens, however, we found that some unique properties of the new specimens are very useful in the field of surface metrology.

Using the new specimens, researchers can make experiments in determining the effects of filter, stylus radius and skid during the measuring process of stylus instruments. For instance, Figure 6 shows the effect of stylus radius, while Figures 5a and 5c show a beneficial effect of skids. Figure 5c was measured without a skid, and Figure 5a was measured at the same place with the skid moving on the smooth reference surface of the specimen. It can be seen that when there was a smooth reference surface supporting the skid motion, the mechanical noise could be reduced significantly.

With the new specimens, researchers can make comparisons of profile graphs among various stylus instruments and determine the range and

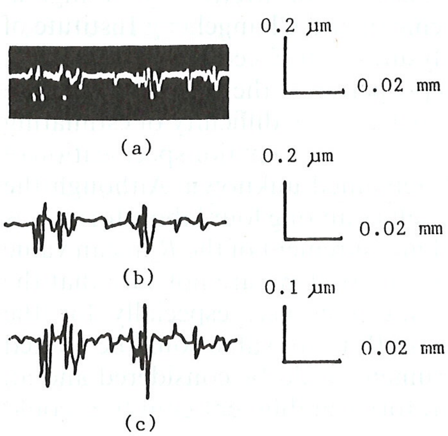

Figure 7 *Profile graphs obtained from stylus instruments and SEM (CIMM specimen no. 1–13, part 1, section B). (a) By SEM JSM–35,* $V_v = 50{,}000\times$*;* $V_h = 500\times$*. (b) By Talysurf-5T,* $V_v = 50{,}000\times$*;* $V_h = 500\times$*;* r = *1.2 µm unfiltered. (c) By Talysurf-4,* $V_v = 100{,}000\times$*;* $V_h = 500\times$*;* r = *2.5 µm unfiltered.*

resolution in both the vertical and horizontal directions, ie. the largest and smallest differences of height that the instrument can measure and the longest and shortest wavelength with which the instrument can cope.[6] For instance, profile graphs shown in Figure 4 were obtained with a Talysurf-4, while Figure 6 was obtained with a Talystep on the same specimen.

The new specimens can be used for setting up connections between optical methods and stylus methods in surface metrology, and making comparisons of the profile graphs obtained from various measuring methods and instruments—for example, stylus instruments and SEM (see Figure 7).

The new specimens can be also used in evaluating instrumentation and computational algorithms designed to measure the surface statistical parameters and functions now being investigated in many laboratories. Some interesting results on the PTB and CIMM specimens were obtained by Mao Qiguang[5] at the China National Institute of Metrology, using the stylus/computer surface roughness measuring system there. One result was that increasing the number of samples (n) in a cutoff length resulted in decreased values of S_m, S, and λ_q for PTB specimens (Figure 8a). However, the values remain at the same level for CIMM specimens (Figure 8b). One conclusion of this work was that the sample interval Δ_s should be no greater than 1 µm, so that the values of S_m, S, and λ_q can be measured with a high confidence.[5]

The new specimens also seem to be useful in tribology, where researchers want to investigate the change of surface topography before, during and after

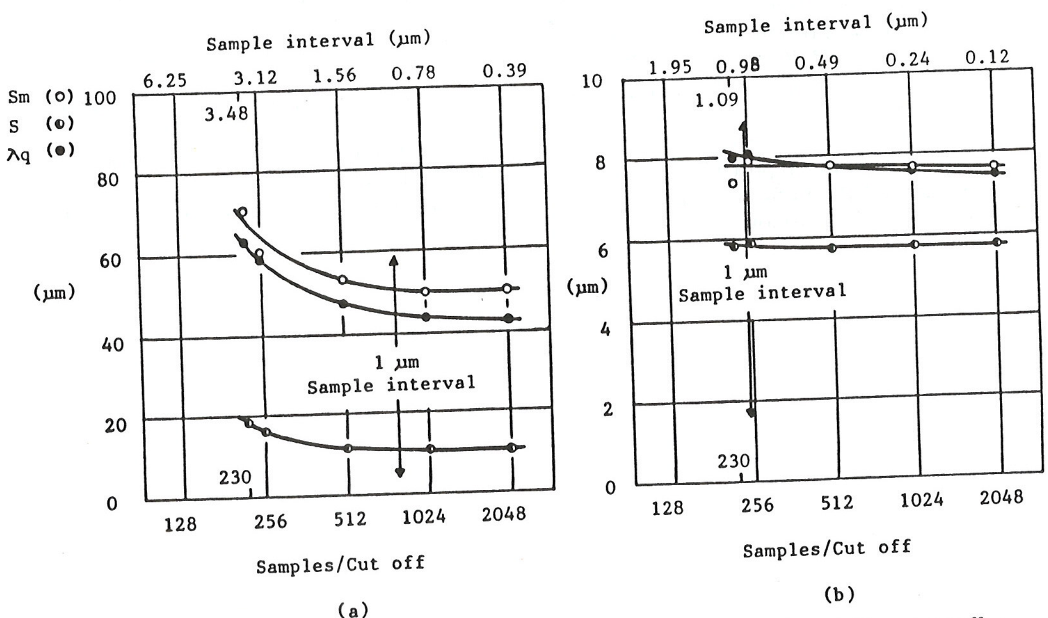

Figure 8 *The effect of sampling intervals. (a) PTB specimen no. 562* ($R_a = 0.53$ *µm; cutoff* = *0.8 mm). (b) CIMM specimen no. 433* ($R_a = 0.116$ *µm; cutoff* = *0.25 mm).*

the rubbing process takes place. To manufacturers, however, the new specimens may also be useful in researching smooth-surface manufacturing techniques.

We plan in the future to continue intercomparison among various laboratories and to improve measuring methods, instruments and conditions, so that measurements of smooth surfaces can be made with a higher degree of precision and agreement.

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