ASME B46.1-1995
(Revision of ANSI/ASME B46.1-1985)

# SURFACE TEXTURE (SURFACE ROUGHNESS, WAVINESS, AND LAY)

AN AMERICAN NATIONAL STANDARD



The American Society of Mechanical Engineers

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Mechanical Engineers

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## ASME B46.1-1995

(Revision of ANSI/ASME B46.1-1985)

Date of Issuance: June 14, 1996

This Standard will be revised when the Society approves the issuance of a new edition. There will be no addenda or written interpretations of the requirements of this Standard issued to this edition.





The American Society of Mechanical Engineers
345 E. 47th Street New York, NY 10017

# FOREWORD

(This Foreword is not part of ASME B46.1-1995.)

The first standard on surface texture was issued in March 1940. The dates for the subsequent changes are as follows:

Revision — February 1947
Revision — January 1955
Revision — September 1962
Revision — August 1971
Revision — March 1978
Revision — March 1985

The current revision is the culmination of a major effort by the ASME Committee B46 on the Classification and Designation of Surface Qualities. A considerable amount of new material has been added, particularly to reflect the increasing number of surface measurement techniques and surface parameters in practical use. Overall, our vision for the ASME B46.1 Standard is twofold:

(*1*) to keep it abreast of the latest developments in the regime of contact profiling techniques where the degree of measurement control is highly advanced, and

(*2*) to encompass a large range of other techniques that present valid and useful descriptions of surface texture.

The present Standard includes nine sections:

Section 1, Terms Related to Surface Texture, contains a number of definitions that are used in other sections of the Standard. Furthermore, a large number of surface parameters are defined in addition to roughness average $R_a$. These include rms roughness $R_q$, waviness height $W_t$, the mean spacing of profile irregularities $S_m$, and several statistical functions, as well as surface parameters for area profiling techniques.

Section 2, Classification of Instruments for Surface Texture Measurement, defines six types of surface-texture measuring instruments including several types of profiling instruments, scanned probe microscopy, and area averaging instruments. With this classification scheme, it is possible that future sections may then provide for the specification on drawings of the type of instrument to be used for a particular surface texture measurement.

Section 3, Terminology and Measurement Procedures for Profiling, Contact, Skidless Instruments, is a new section based on proposals in ISO Technical Committee 57 to define the characteristics of instruments that directly measure surface profiles, which then can serve as input data to the calculations of surface texture parameters.

Section 4, Measurement Procedures for Contact, Skidded Instruments, contains much of the information that was previously contained in ASME B46.1-1985 for specification of instruments primarily intended for measurement of averaging parameters such as the roughness average $R_a$.

Section 5, Measurement Techniques for Area Profiling, is a new section that lists a number of techniques, many of them developed since the mid 1980's, for three-dimensional surface mapping. Because of the diversity of techniques, very few recommendations can be given in Section 5 at this time to facilitate uniformity of results between different techniques. However, this section does allow for the measurement of the area profiling parameters, $AR_a$ and $AR_q$, as alternatives to the traditional profiling parameters.

Section 6, Measurement Techniques for Area Averaging, updates recommendations first stated in the previous revision, ASME B46.1-1985, allowing for the use of area averaging techniques as comparators to distinguish the surface texture of parts manufactured by similar processes. In future sections, surface parameters based directly on these techniques may be defined or surface specifications may be proposed that call for measurements by these types of instruments.

Sections 7 and 8 have been reserved to accommodate future paragraphs relating to instruments and procedures.

Section 9, Filtering of Surface Profiles, carries on with the traditional specifications of the 2RC cutoff filter and introduces the phase corrected Gaussian filter as well as band-pass roughness concepts.

Section 10 has been reserved to accommodate future paragraphs.

Section 11, Specifications and Procedures for Precision Reference Specimens, describes a number of different types of specimens useful in the calibration and testing of surface profiling instruments. It is based on ISO 5436, Calibration Specimens-Stylus Instruments-Types, Calibration, and Use of Specimens, but contains new information as well.

Section 12, Specifications and Procedures for Roughness Comparison Specimens, describes specimens that are useful for the testing and characterization of area averaging instruments.

Approximately 30 people have written, edited, and reviewed this Standard. However, with such an extensive revision, inconsistencies in the definitions or recommendations may have been overlooked. The user is invited to submit any comments or suggestions to ASME.

Secretary, B46 Committee
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The committee is actively working on another revision of this Standard and on an additional standard that will contain recommendations for surface texture measurements at the nanometer level.

This Standard was approved as an American National Standard on June 26, 1995.

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## CONTENTS

**Figures**

**Tables**

**Appendices**



**Figures**

# SURFACE TEXTURE (SURFACE ROUGHNESS, WAVINESS, AND LAY)

## SECTION 1 TERMS RELATED TO SURFACE TEXTURE

### 1.1 General

**1.1.1 Scope.** This Standard is concerned with the geometric irregularities of surfaces. It defines surface texture and its constituents: roughness, waviness, and lay. It also defines parameters for specifying surface texture.

The terms and ratings in this Standard relate to surfaces produced by such means as abrading, casting, coating, cutting, etching, plastic deformation, sintering, wear, erosion, etc.

**1.1.2 Limitations.** This Standard is not concerned with error of form and flaws, but discusses these two factors to distinguish them from surface texture.

This Standard is not concerned with luster, appearance, color, corrosion resistance, wear resistance, hardness, subsurface microstructure, surface integrity, and many other characteristics which may govern functional considerations in specific applications.

This Section does not recommend specific surface roughness, waviness, or type of lay suitable for specific purposes, nor does it specify the means by which these irregularities may be obtained or produced. Criteria for selection of surface qualities and information on instrument techniques and methods of producing, controlling, and inspecting surfaces are included in the other sections and in the appendices. The appendices shall not be considered a part of this Standard. They are included for clarification and information purposes only.

Surface texture designations as delineated in this Standard may not provide a sufficient set of indexes for describing performance. Other characteristics of engineering components such as dimensional and geometrical characteristics, material, metallurgy, and stress must also be controlled.

**1.1.3 SI Values.** Values of quantities stated in the SI[1] (metric) system are to be regarded as standard. Approximate nonmetric equivalents are shown for reference.

**1.1.4 References.** This Standard is to be used in conjunction with ASME Y14.36M, Surface Texture Symbols, which prescribes engineering drawing and related documentation practices for specifying surface texture. Other relevant standards, which should be used in design and measurement, are:

ASME B89.6.2-1973 (R1988), Temperature and Humidity Environment for Dimensional Measurement

ASME Y14.5M-1994, Dimensioning and Tolerancing, Engineering Drawings and Related Documentation Practices

The above standards are available from ASME Order Department, 22 Law Drive, Box 2300, Fairfield, NJ 07007-2300.

References to other useful works are included as footnotes.

**1.1.5 Cleanliness.** Normally, surfaces to be measured should be free of any foreign material that would interfere with the measurement.

### 1.2 Definitions Related to Surfaces

**1.2.1 Surfaces**

*surface* — the boundary that separates an object from another object, substance, or space

*nominal surface* — the intended surface boundary (exclusive of any intended surface roughness), the shape and extent of which is usually shown and dimensioned on a drawing or descriptive specification (See Fig. 1-1.)

*real surface* — the actual boundary of an object. Its deviations from the nominal surface stem from the processes that produce the surface.

*measured surface* — a representation of the real surface obtained by the use of a measuring instrument

[1] Le Système International d'Unités.

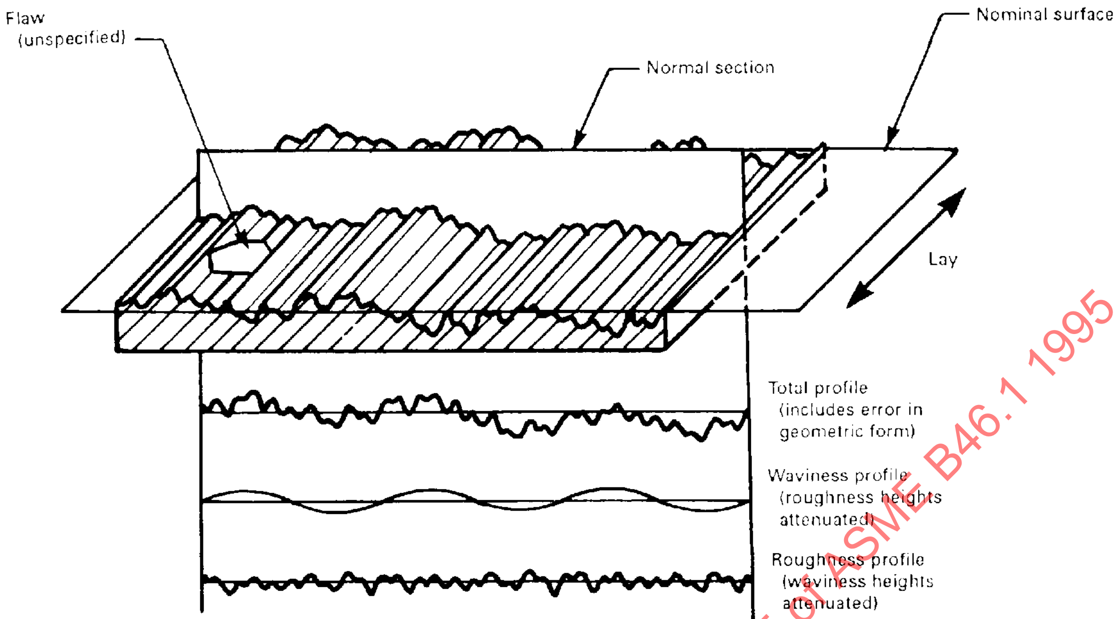



FIG. 1-1 SCHEMATIC DIAGRAM OF SURFACE CHARACTERISTICS



**1.2.2 Components of the Real Surface.** The real surface differs from the nominal surface to the extent that it exhibits surface texture, flaws, and errors of form. It is considered as the linear superposition of roughness, waviness, and form with the addition of flaws.

*roughness* — the finer irregularities of the surface texture that usually result from the inherent action of the production process or material condition. These might be characteristic marks left by the processes listed in Fig. B1 of Appendix B.

*waviness* — the more widely spaced component of the surface texture. Waviness may be caused by such factors as machine or workpiece deflections, vibration, and chatter. Roughness may be considered as superimposed on a wavy surface.

*lay* — the predominant direction of the surface pattern, ordinarily determined by the production method used

*surface texture* — the composite of certain deviations that are typical of the real surface. It includes roughness and waviness.

*error of form* — widely spaced deviations of the real surface from the nominal surface, which are not included in surface texture. The term is applied to deviations caused by such factors as errors in machine tool ways, guides, or spindles, insecure clamping or incorrect alignment of the workpiece, or uneven wear. Out-of-flatness and out-of-roundness[2] are typical examples.

*flaws* — unintentional, unexpected, and unwanted interruptions in the topography typical of a surface. *Topography* is defined in para. 1.5.1. However, these topographical interruptions are considered to be flaws only when agreed upon in advance by buyer and seller. If flaws are specified, the surface should be inspected by some mutually agreed upon method to determine whether flaws are present and are to be rejected or accepted prior to performing final surface roughness measurements. If specified flaws are not present, or if flaws are not specified, then interruptions in the surface topography of an engineering component may be included in roughness measurements.

[2] ASME/ANSI B89.3.1-1972 (R 1988), Measurement of Out-of-Roundness.

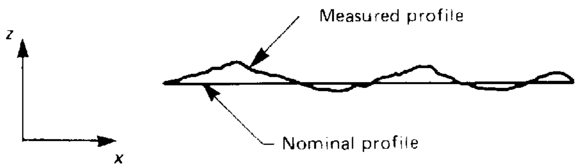



**FIG. 1-2 MEASURED VS NOMINAL PROFILE**

## 1.3 Definitions Related to the Measurement of Surface Texture by Profiling Methods

The features defined above are inherent to surfaces and are independent of the method of measurement. Methods of measurement of surface texture can be classified generally as contact or noncontact methods and as three-dimensional (area) or two-dimensional (profile) methods.

### 1.3.1 Profiles

*profiling method* — a surface scanning measurement technique that produces a two-dimensional graph or profile of the surface irregularities as measurement data

*profile* — the curve of intersection of a normal sectioning plane with the surface (See Fig. 1-1.)

*nominal profile* — a profile of the nominal surface: a straight line or smooth curve

*real profile* — a profile of the real surface

*measured profile* — a representation of the real profile obtained by a measuring instrument (see Fig. 1-2). The profile is usually drawn in a $x$-$z$ coordinate system.

*modified profile* — a measured profile for which filter mechanisms (electrical, mechanical, optical, or digital) are used to minimize certain surface-texture characteristics and emphasize others. Modified profiles differ from unmodified, measured profiles in ways that are selectable by the instrument user, usually for the purpose of distinguishing surface roughness from surface waviness.

By previous definition (see para. 1.2.2), roughness irregularities are more closely spaced than waviness irregularities. Roughness can thus be distinguished from waviness in terms of spatial wavelengths along the path traced. See para. 1.3.4 for a definition of spatial wavelength. No unique spatial wavelength is defined that would distinguish roughness from waviness for all surfaces.

*roughness profile* — the modified profile obtained by filtering to attenuate the longer spatial wavelengths associated with waviness (See Fig. 1-1.)

*waviness profile* — the modified profile obtained by filtering to attenuate the shorter spatial wavelengths associated with roughness and the longer spatial wavelengths associated with the part form

*total profile* — a measured profile in which profile heights and spacings may be amplified differently, but in which no other intentional modification or filtering has been carried out

**1.3.1.1 Aspect Ratio.** In displays of surface profiles generated by instruments, height deviations from the geometric profile are usually magnified many times more than distances along the geometric profile (see Fig. 1-3).[3] The sharp peaks and valleys and the steep slopes seen on such profile representations of surfaces are thus greatly distorted images of the relatively gentle slopes characteristic of actual measured profiles.

### 1.3.2 Reference Mean Lines

*mean line (M)* — the reference line about which the profile deviations are measured. The mean line may be determined in several ways as discussed below.

*least squares mean line* — a line having the form of the nominal profile and dividing the profile so that, within a selected length, the sum of the squares of the profile deviations from this line is minimized. The form of the nominal profile could be a straight line or a curve (see Fig. 1-4).

*filtered mean line* — the mean line established by the selected cutoff filter (see para. 1.3.5) and its associated analog or digital circuitry in a surface mea-

[3] R. E. Reason, *Modern Workshop Technology, 2 — Processes*, H. W. Baker, ed., 3rd edition (London: Macmillan, 1970), Chap. 23.

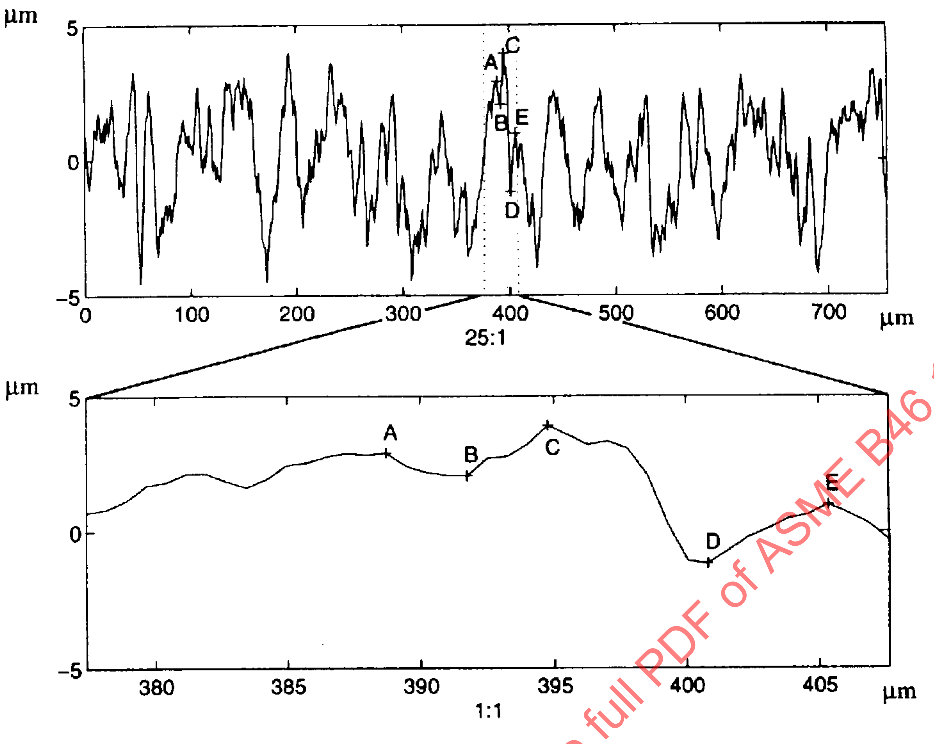



FIG. 1-3 STYLUS PROFILE DISPLAYED WITH TWO DIFFERENT ASPECT RATIOS



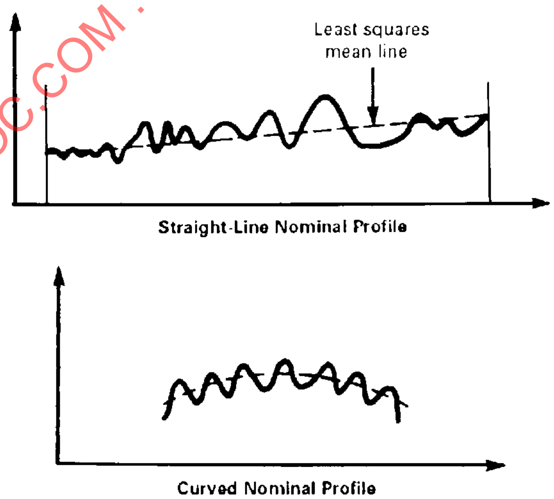
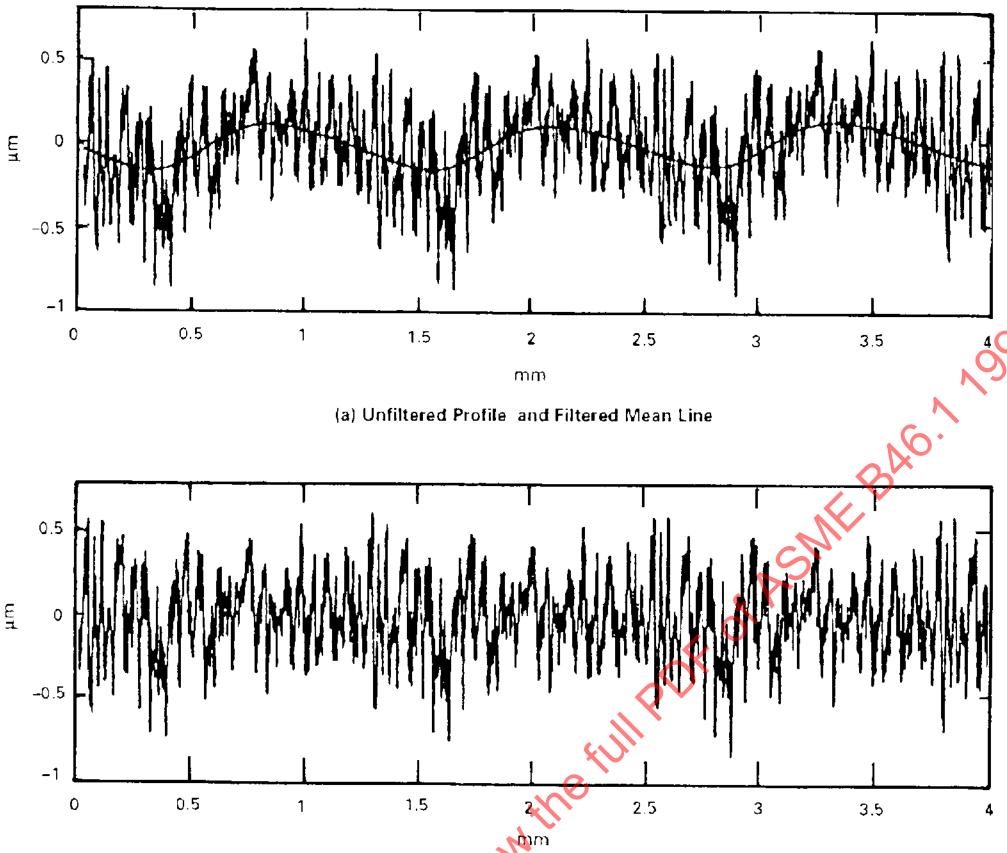



FIG. 1-4 EXAMPLES OF NOMINAL PROFILES




(a) Unfiltered Profile and Filtered Mean Line

(b) Roughness Profile

**FIG. 1-5 FILTERING A SURFACE PROFILE**



suring instrument. Figure 1-5 illustrates the electrical filtering of a surface profile. It shows the unfiltered profile in Fig. 1-5(a) along with the filtered mean line or waviness profile. The difference between them is the roughness profile shown in Fig. 1-5(b).

### 1.3.3 Peaks and Valleys, Height Resolution, and Height Range

*profile peak* — the point of maximum height on a portion of a profile that lies above the mean line and between two intersections of the profile with the mean line (See Fig. 1-6.)

*profile valley* — the point of maximum depth on a portion of a profile that lies below the mean line and between two intersections of the profile with the mean line (See Fig. 1-6.)

*profile irregularity* — a profile peak and the adjacent profile valley

*system height (z) resolution* — the minimum step height that can be distinguished from background noise by a measuring system. This is a key specification for a measuring instrument. The system background noise can be evaluated by measuring the apparent rms roughness of a surface whose actual roughness is significantly smaller than the system background noise.

*height (z) range* — the largest overall peak-to-valley surface height that can be accurately detected by a

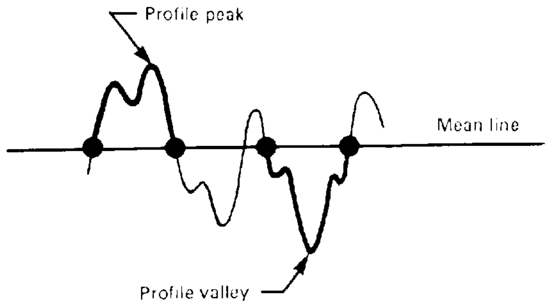



FIG. 1-6 PROFILE PEAK AND VALLEY

measuring instrument. This is a key specification for a measuring instrument.

### 1.3.4 Spacings

*spacing* — the distance between specified points on the profile measured along the nominal profile

*roughness spacing* — the average spacing between adjacent peaks of the measured roughness profile within the roughness sampling length (defined in para. 1.3.5)

*waviness spacing* — the average spacing between adjacent peaks of the measured waviness profile within the waviness long-wavelength cutoff (defined in Section 9)

*spatial wavelength*, $\lambda$ — the spacing between adjacent peaks of a purely sinusoidal profile

*spatial (x) resolution* — for an instrument, the smallest surface spatial wavelength that can be resolved to 50% of its actual amplitude. This is determined by such characteristics of the measuring instrument as the sampling interval (defined below), radius of the stylus tip, or optical probe size. This is a key specification for a measuring instrument.

NOTE: Concerning resolution, the sensitivity of an instrument to measure the heights of small surface features may depend on the combination of the spatial resolution and the feature spacing,[4] as well as the system height resolution.

*sampling interval*, $d_o$ — the lateral point-to-point spacing of a digitized profile (see Fig. 1-8). The minimum spatial wavelength to be included in the profile analysis should be at least five times the sampling interval.

### 1.3.5 Sampling Lengths

*sampling length* — the nominal interval within which a single value of a surface parameter is determined. It corresponds approximately to the longest spatial wavelength of profile deviation to be included in the profile analysis. This is different from the evaluation length and the traversing length (see para. 1.3.6). The range of sampling lengths is a key specification for a measuring instrument.

*roughness sampling length*,[5] *l* — the sampling length specified to separate the profile irregularities designated as roughness from those irregularities designated as waviness. The roughness sampling length may be determined by electrical analog filtering, digital filtering, or geometrical truncation of the profile into the appropriate lengths.

*roughness long-wavelength cutoff*,[6] $\lambda_c$ — the nominal rating in millimeters (mm) of the electrical or digital filter that attenuates the long wavelengths of the surface profile to yield the roughness profile (See Sections 3, 4, and 9.)

*waviness sampling length* — This concept is no longer used. See *waviness long-wavelength cutoff* and *waviness evaluation length* (defined in Section 9).

*waviness short-wavelength cutoff*, $\lambda_s$ — the nominal rating in millimeters of the electrical or digital filter that attenuates the short wavelengths (roughness) of the surface profile to yield the waviness profile (see Sections 3 and 4). It should be equal to the roughness long-wavelength cutoff.

### 1.3.6 Overall Measurement Lengths

*evaluation length*, $L$ — the length over which the values of surface parameters are evaluated. For proper statistics it should contain a number of sampling lengths (see Fig. 1-7). In some standards, five sampling lengths are recommended as comprising one evaluation length. However, for certain types of instruments or certain measurements, the evaluation

[4] J. M. Bennett and L. Mattsson, *Introduction to Surface Roughness and Scattering* (Washington, DC: Optical Society of America, 1989), 22.

[5] See also Sections 4 and 9 and Appendix A.

[6] In most electrical averaging instruments, the cutoff can be selected. It is a characteristic of the instrument rather than the surface being measured. In specifying the cutoff, care must be taken to choose a value which will include all the surface irregularities that one desires to evaluate.

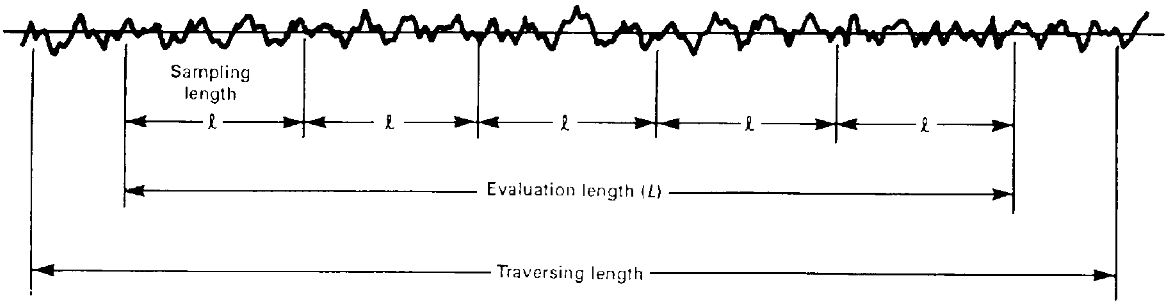



**FIG. 1-7 SURFACE PROFILE MEASUREMENT LENGTHS**

length may comprise only one sampling length. See Sections 3 and 4 for values which are recommended for different types of roughness and waviness measurements. The evaluation length is a key specification for a measuring instrument.

*traversing length* — the length of profile which is traversed by a profiling instrument to establish a representative evaluation length. Because of end effects in profile measurements, the traversing length must be longer than the evaluation length (see Fig. 1-7).

## 1.4 Definitions of Surface Parameters for Profiling Methods

Key quantities that distinguish one profile from another are their height deviations from the nominal profile and the distances between comparable deviations. Various mathematical combinations of surface profile heights and spacings have been devised to compare certain features of profiles numerically.

### 1.4.1 Height (z) Parameters

*height parameter* — a general term used to describe a measurement of the profile taken in a direction normal to the nominal profile. Height parameters are expressed in micrometers ($\mu$m).[7]

[7]A micrometer is one millionth of a meter (0.000001 m). A microinch is one millionth of an inch (0.000001 in.). For written specifications or reference to surface roughness requirements, micrometer can be abbreviated as $\mu$m, and microinch may be abbreviated as $\mu$in. One microinch equals 0.0254 $\mu$m ($\mu$in. = 0.0254 $\mu$m). The nanometer (nm) and the angstrom unit (Å) are also used in some industries. 1 nm = 0.001 $\mu$m, 1Å = 0.1 nm.

#### 1.4.1.1 Roughness Height Parameters

*profile height function, $Z(x)$* — the function used to represent the point-by-point deviations between the measured profile and the reference mean line (see Fig. 1-8). For digital instruments, the profile $Z(x)$ is approximated by a set of digitized values ($Z_i$) recorded using the sampling interval ($d_o$).

*roughness average,*[8] $R_a$ — the arithmetic average of the absolute values of the profile height deviations recorded within the evaluation length and measured from the mean line. As shown in Fig. 1-8, $R_a$ is equal to the sum of the shaded areas of the profile divided by the evaluation length $L$, which generally includes several sampling lengths or cutoffs. For graphical determinations of roughness, the height deviations are measured normal to the chart center line.

Analytically, $R_a$ is given by:

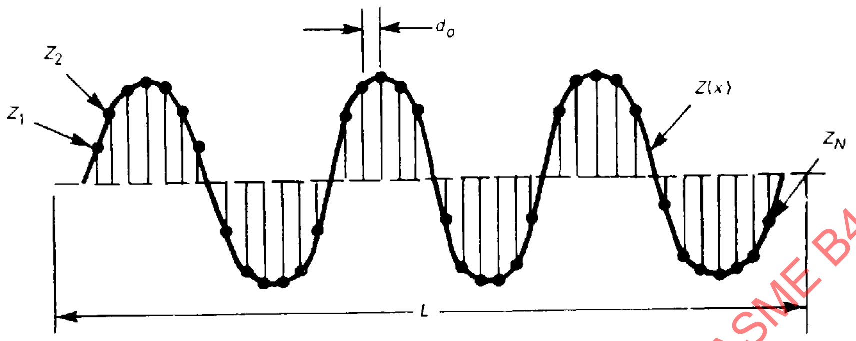
$$R_a = (1/L)\int_0^L |Z(x)|dx$$

For digital instruments an approximation of the $R_a$ value may be obtained by adding the individual $Z_i$ values without regard to sign and dividing the sum by the number of data points $N$.

$$R_a = (|Z_1| + |Z_2| + |Z_3| \cdots |Z_N|)/N$$

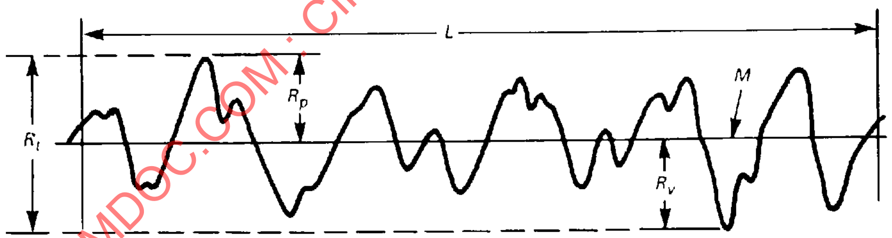
*root mean square (rms) roughness, $R_q$* — the root mean square average of the profile height deviations

[8]Roughness average is also known as center line arithmetic average (AA) and center line average (CLA).




$R_a$ = Average deviation of roughness profile $Z(x)$ from the mean line
= Total shaded area/$L$

**FIG. 1-8 ILLUSTRATION FOR THE CALCULATION OF ROUGHNESS AVERAGE $R_a$**




GENERAL NOTE: The mean line is denoted by $M$.

**FIG. 1-9 $R_t$, $R_p$, AND $R_v$ PARAMETERS**

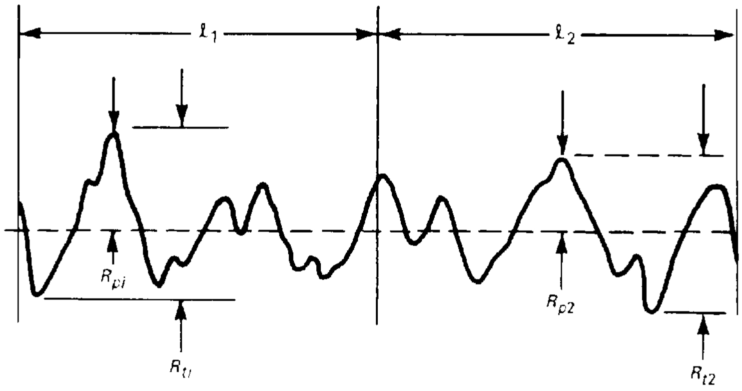



**FIG. 1-10 SURFACE PROFILE CONTAINING TWO SAMPLING LENGTHS, $l_1$ AND $l_2$, ALSO SHOWING THE $R_{pi}$ AND $R_{ti}$ PARAMETERS**

taken within the evaluation length and measured from the mean line. Analytically, it is given by:

$$R_q = \left[ (1/L) \int_0^L Z(x)^2 \, dx \right]^{1/2}$$

The digital approximation is:

$$R_q = [(Z_1^2 + Z_2^2 + Z_3^2 + \cdots + Z_N^2)/N]^{1/2}$$

*maximum profile peak height,* $R_p$ — the distance between the highest point of the profile and the mean line within the evaluation length (See Fig. 1-9.)

*maximum profile valley depth,* $R_v$ — the distance between the lowest point of the profile and the mean line within the evaluation length (See Fig. 1-9.)

*maximum height of the profile,* $R_t$ — the vertical distance between the highest and lowest points of the profile within the evaluation length (See Fig. 1-9.)

$$R_t = R_p + R_v$$

In the DIN Standard 4768, the evaluation length consists of five sampling lengths.[9]

[9]Deutsche Normen DIN 4768, *Determination of Surface Roughness Values $R_a$, $R_z$, $R_{max}$, with Electric Stylus Instruments — Basic Data* (Berlin: Beuth Verlag, GmbH, 1974).

$R_{pi}$ — the distance between the highest point of the profile and the mean line within a sampling length segment labelled *i* (See Fig. 1-10.)

*average maximum profile peak height,* $R_{pm}$ — the average of the successive values of $R_{pi}$ calculated over the evaluation length. This parameter is the same as $R_{pm}$ (DIN) when there are five sampling lengths within an evaluation length.

$R_{ti}$ — the vertical distance between the highest and lowest points of the profile within a sampling length segment labelled *i* (See Fig. 1-10.)

*average maximum height of the profile,* $R_z$ — the average of the successive values of $R_{ti}$ calculated over the evaluation length. This parameter is the same as $R_z$(DIN)[9] when there are five sampling lengths within an evaluation length.

*maximum roughness depth,* $R_{max}$ — the largest of the successive values of $R_{ti}$ calculated over the evaluation length. In the DIN Standard 4768, the evaluation length consists of five sampling lengths[9] (see Fig. 1-11). $R_{max}$ is also called $R_{ymax}$ in ISO documents.

$H_{tp}$ — a height parameter defined in terms of bearing length ratios (See para. 1.4.3.)

#### 1.4.1.2 Waviness Height Parameters

*waviness height,* $W_t$ — the peak-to-valley height of the modified profile from which roughness and part form have been removed by filtering, smoothing, or other means (see Fig. 1-12). The measurement is to be taken normal to the nominal profile within the limits of the waviness evaluation length.

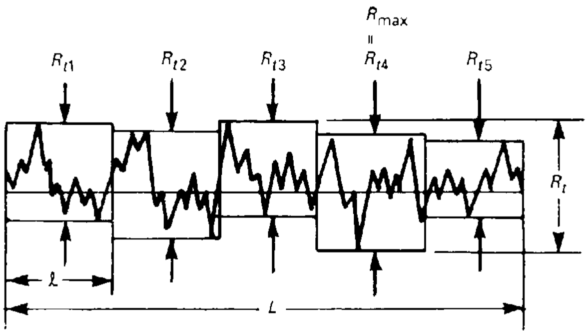



FIG. 1-11 THE $R_t$ AND $R_{max}$ PARAMETERS

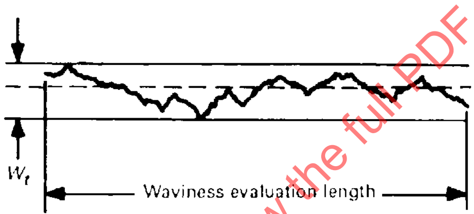



FIG. 1-12 THE WAVINESS HEIGHT, $W_t$

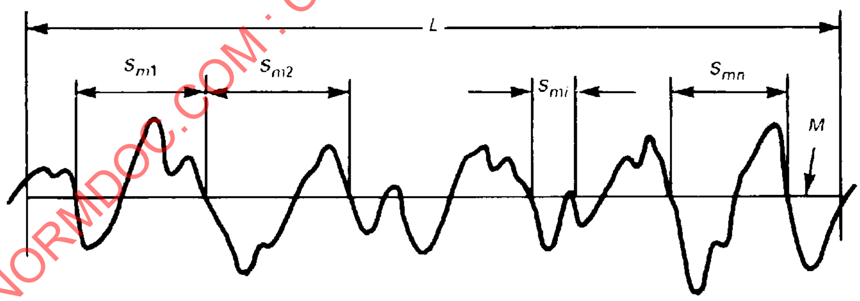



FIG. 1-13 THE MEAN SPACING OF PROFILE IRREGULARITIES, $S_m$

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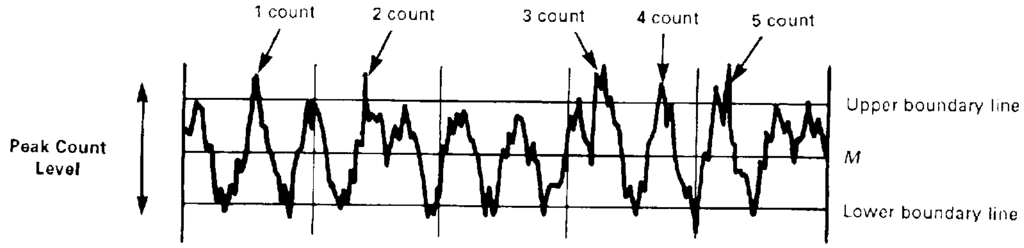



**FIG. 1-14 THE PEAK COUNT LEVEL, USED FOR CALCULATING PEAK DENSITY**



### 1.4.2 Spacing Parameters

*spacing parameter* — a distance that characterizes the lateral spacings between the individual profile asperities

*mean spacing of profile irregularities*, $S_m$ — the mean value of the spacing between profile irregularities within the evaluation length. In Fig. 1-13:

$$S_m = (1/n) \sum_{i=1}^{n} S_{mi}$$

*SAE peak*[10] — a profile irregularity wherein the profile intersects consecutively a lower and an upper boundary line. The boundary lines are located parallel to and equidistant from the profile mean line (see Fig. 1-14), and are set by a designer or an instrument operator for each application.

*peak count level*[10] — the vertical distance between the boundary lines described in the definition of *SAE peak* (See Fig. 1-14.)

*peak density*,[10] $P_c$ — the number of SAE peaks per unit length measured at a specified peak count level

### 1.4.3 Shape Parameters and Functions

*amplitude density function*, ADF($z$) or $p(z)$ — the probability density of surface heights. The amplitude density function is normally calculated as a histogram of the digitized points on the profile (see Fig. 1-15).

*profile bearing length* — the sum of the section lengths obtained by cutting the profile peaks by a line parallel to the mean line within the evaluation length at a specified level $p$. The level $p$ may be specified in several ways including:

(*1*) as a depth from the highest peak (with an optional offset);

(*2*) as a height from the mean line; or

(*3*) as a percentage of the $R_t$ value relative to the highest peak (see Fig. 1-16).

*profile bearing length ratio*, $t_p$ — the ratio of the profile bearing length to the evaluation length at a specified level $p$. The quantity $t_p$ should be expressed in %.

$$t_p = \frac{b_1 + b_2 + b_3 + \cdots + b_n}{L} \times 100\%$$

*bearing area curve*, BAC — the cumulative distribution of the ADF, also called the Abbott-Firestone curve. It shows how the profile bearing length ratio varies with level.

$H_{tp}$ — difference in the heights for two profile bearing length ratios $t_p$ set at selectable values (See Fig. 1-17.)

*skewness*, $R_{sk}$ — a measure of the asymmetry of the profile about the mean line (see Fig. 1-18). In analytic form:

$$R_{sk} = \frac{1}{R_q^3} \frac{1}{L} \int_0^L Z^3(x)dx$$

For a digitized profile, a useful formula is:

$$R_{sk} = \frac{1}{R_q^3} \frac{1}{N} \sum_{j=1}^{N} Z_j^3$$

[10]Adapted from *SAE Handbook Vol. 1, Materials* (Warrendale: Society of Automotive Engineers, 1981) SAE J911, Chap. 9.

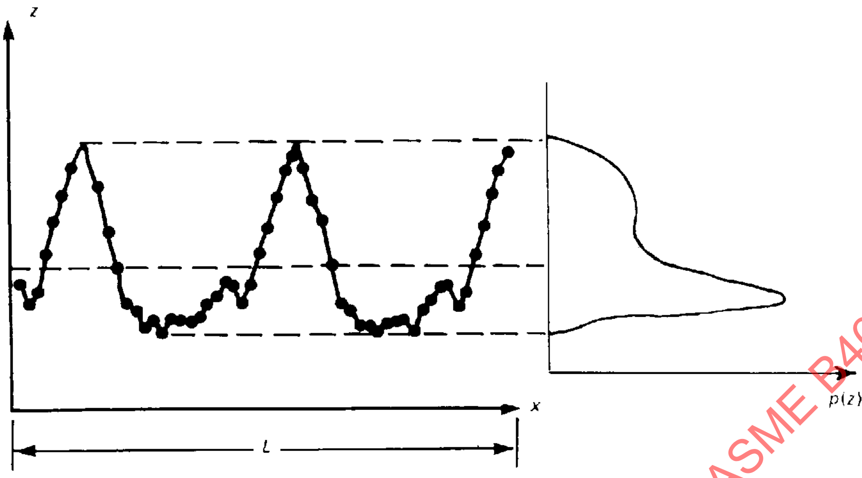



**FIG. 1-15 AMPLITUDE DENSITY FUNCTION — ADF(z) OR p(z)**

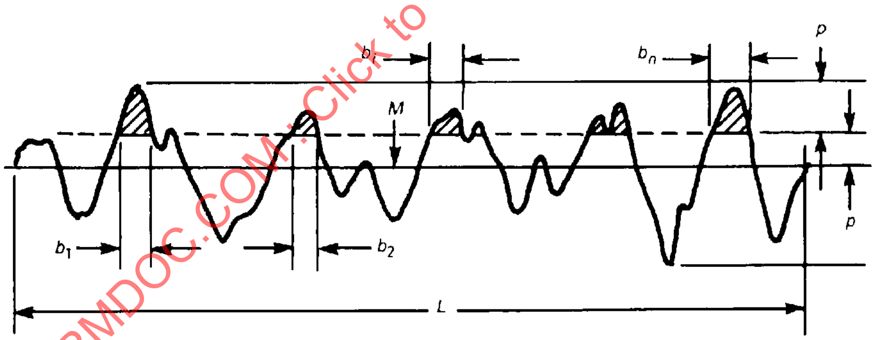
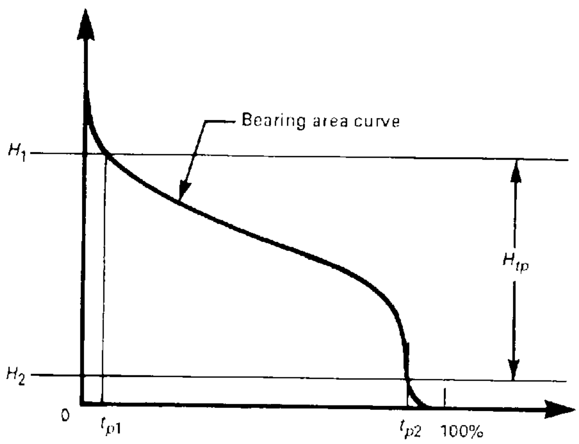


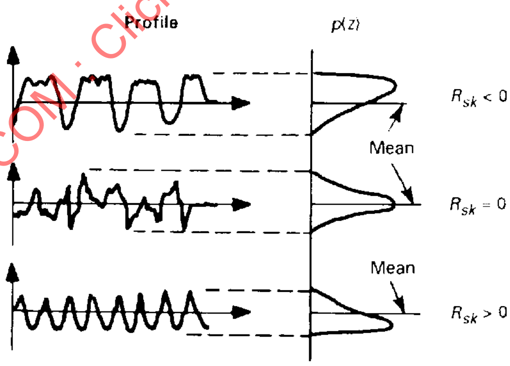

**FIG. 1-16 THE PROFILE BEARING LENGTH**




$t_{p1}$, $t_{p2}$ = Selected profile bearing length ratios
$H_1$, $H_2$ = Levels for $t_{p1}$ and $t_{p2}$
$H_{tp}$ = Height between bearing ratios

**FIG. 1-17 THE BEARING AREA CURVE AND RELATED PARAMETERS**






GENERAL NOTE:
Three surfaces with different skewness. Also shown are the amplitude density functions (histograms) of surface height.

**FIG. 1-18 THREE SURFACE PROFILES WITH DIFFERENT SKEWNESS**

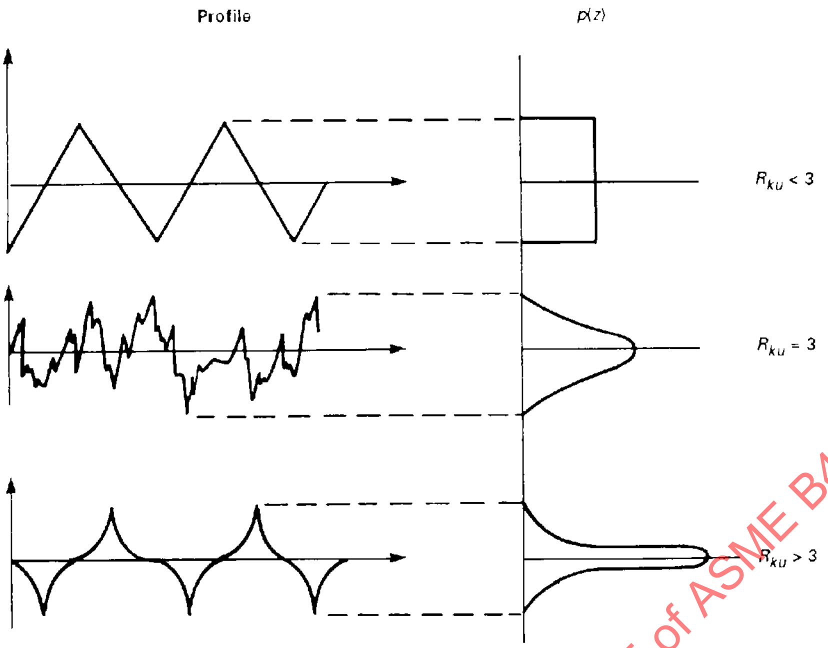



**FIG. 1-19 THREE SURFACE PROFILES WITH DIFFERENT KURTOSIS**

*kurtosis*, $R_{ku}$ — a measure of the peakedness of the profile about the mean line (see Fig. 1-19). In analytic form:

$$R_{ku} = \frac{1}{R_q^4}\frac{1}{L}\int_0^L Z^4(x)dx$$

For a digitized profile, a useful formula is:

$$R_{ku} = \frac{1}{R_q^4}\frac{1}{N}\sum_{j=1}^{N} Z_j^4$$

NOTE: The calculated values of skewness and kurtosis are very sensitive to outliers in the surface profile data.

*power spectral density*, PSD($f$) — the Fourier decomposition of the measured surface profile into its component spatial frequencies ($f$). The function may be defined analytically by:[11]

$$\mathrm{PSD}(f) = \lim_{L\to\infty} (1/L) \left| \int_{-L/2}^{L/2} Z(x)e^{-i2\pi f x}\, dx \right|^2$$

where the expression inside the absolute value symbols approaches the Fourier transform of the surface profile $Z(x)$ when $L \to \infty$. For a digitized profile of length $L$, consisting of $N$ equidistant points separated by a sampling interval $d_o$, the function may be approximated by:

$$\mathrm{PSD}(f) = (d_o/N) \left| \sum_{j=1}^{N} Z_j\, e^{-i2\pi f (j-1) d_o} \right|^2$$

where $i = \sqrt{-1}$, the spatial frequency $f$ is equal to $K/L$, and $K$ is an integer that ranges from 1 to N/2. The PSD may also be calculated by taking the Fourier transform of the autocovariance function discussed next.

*autocovariance function*, ACV($\tau$) — The ACV is given by an overlap integral of shifted and unshifted profiles and is also equal to the inverse Fourier transform of the PSD. The ACV is given by:

$$\mathrm{ACV}(\tau) = \lim_{L\to\infty} (1/L) \int_{-L/2}^{L/2} Z(x)\, Z(x + \tau)\, dx$$

[11] R. B. Blackman and J. W. Tukey, *The Measurement of Power Spectra* (New York: Dover, 1958), 5–9.

where $\tau$ is the shift distance. For a finite, digitized profile, it may be approximated by:

$$\mathrm{ACV}(\tau) = \frac{1}{N} \sum_{j=1}^{N-j'} Z_j Z_{j+j'}$$

where $\tau = j' d_o$.

*autocorrelation function*, ACF($\tau$) — The normalized autocovariance function:[11]

$$\mathrm{ACF}(\tau) = \mathrm{ACV}(\tau)/R_q^2$$

*correlation length* — the shift distance at which the autocorrelation function falls to a selected value. Typical selected values are $1/e$ (the base of the natural logarithms) or 0.1 or 0 (the first zero crossing).

### 1.4.4 Hybrid Parameters

*average absolute slope*, $\Delta_a$ — the arithmetic average of the absolute value of the rate of change of the profile height calculated over the evaluation length. Analytically, it may be given by:

$$\Delta_a = (1/L) \int_0^L |dZ/dx| dx$$

where $|dZ/dx|$ is the local slope of the profile. Digitally, it may be given by:

$$\Delta_a = \frac{1}{N} \sum_{i=1}^{N} |\Delta_i|$$

where

$$\Delta_i = \frac{1}{60 d_o} (Z_{i+3} - 9Z_{i+2} + 45Z_{i+1} - 45Z_{i-1} + 9Z_{i-2} - Z_{i-3})$$

The selected value of $d_o$ influences the value of $\Delta_a$.

*root mean square slope*, $\Delta_q$ — the root mean square average of the rate of change of the profile height calculated over the evaluation length. Analytically, it may be given by:

$$\Delta_q = \left(1/L \int_0^L (dZ/dx)^2 \, dx\right)^{1/2}$$

Digitally, it may be given by:

$$\Delta_q = \left[\frac{1}{N} \sum_{i=1}^{N} (\Delta_i)^2\right]^{1/2}$$

where $\Delta_i$ is given above. Just as for the average slope $\Delta_a$, the selected value of $d_o$ influences the value of $\Delta_q$.

## 1.5 Definitions Related to the Measurement of Surface Texture by Area Profiling and Area Averaging Methods

**1.5.1 General.** Several types of surface measurement techniques are used to quantify the surface texture over a selected area of a surface instead of over single profiles. Area methods may be divided into two classes, area profiling methods and area averaging methods, as defined below.

*area profiling method* — a surface measurement method by which the topographic information is represented as a height function $Z(x,y)$ of two independent variables $(x,y)$. Ordinarily, the function $Z(x,y)$ is developed by juxtaposing a set of parallel profiles as shown in Fig. 1-20. The height function $Z(x,y)$ is defined in para. 1.6.1.

*area averaging method* — a technique that measures a representative area of a surface and produces quantitative results that depend on area averaged properties of the surface texture. Such techniques include parallel plate capacitance and optical scattering.

*topography* — the three-dimensional representation of geometric surface irregularities (See Fig. 1-20.)

*nominal surface* — See para. 1.2.1.

*real surface* — See para. 1.2.1.

*measured topography* — a three-dimensional representation of the real surface obtained by a measuring instrument

*modified topography* — a three-dimensional representation of the real surface obtained by a measuring instrument for which filtering mechanisms (electrical, mechanical, optical, or digital) are used to minimize certain surface texture characteristics and emphasize others

*roughness topography* — the modified topography obtained by attenuating the longer surface wavelengths associated with waviness

*waviness topography* — the modified topography obtained by attenuating the shorter surface wavelengths associated with roughness and the longer wavelengths associated with the part form

**1.5.2 Reference Mean Surfaces**

*mean surface* — the three-dimensional reference surface about which the topographic deviations are

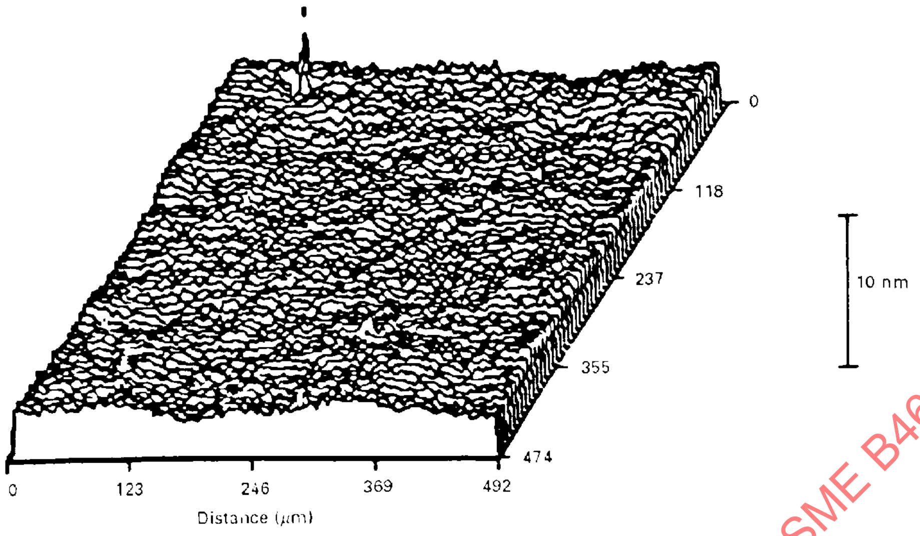



**FIG. 1-20 TOPOGRAPHIC MAP OBTAINED BY AN AREA PROFILING METHOD**



measured. The mean surface may be determined in several ways, as described below.

*least squares mean surface* — a surface having the general form of the nominal surface such that, within a specified area, the sum of the squares of the topography deviations from this surface is minimized

*filtered mean surface* — the surface established by applying a filtering process to the measured topography. The filtering techniques may be electrical, mechanical, optical, or digital. Some examples are a Fourier filter, a polynomial fit using least squares techniques, or a directional based filter to eliminate or enhance directional surface features such as lay.

**1.5.3 Area Peaks and Valleys**

*area peak* — the point of maximum height on a topography in an area bounded by the intersection of the topography with the mean surface; the area analog of a profile peak (See Fig. 1-21.)

*area valley* — the point of maximum depth on a topography in an area bounded by the intersection of the topography with the mean surface; the area analog of a profile valley (See Fig. 1-21.)

**1.5.4 Sampling Areas.** Sampling areas for area profiling methods are conceptually similar to sampling lengths for ordinary profiling methods (see para. 1.3.5). In particular, the following concepts are useful.

*sampling area, $A_s$* — the area within which a single value of a surface parameter is determined. The characteristic dimension of the sampling area should at least be equal to the maximum spatial wavelength to be quantified.

*minimum resolvable area* — the area analog of spatial resolution. This is usually determined by the capabilities of the measuring instrument by such factors as the sampling interval (see para. 1.3.4), radius of the stylus tip, or optical resolution. The lateral resolution may not be the same in every direction. For example, in a raster scanning system, an instrument may have a very small sampling interval along the direction of each scan line, but may have a large spacing between adjacent scan lines.

*evaluation area, $A_e$* — the total area over which the values of surface parameters are evaluated. For proper statistics, it may contain a number of sampling areas. $A_e = L_x L_y$ for a rectangular, raster scanned area.

## 1.6 Definitions of Surface Parameters for Area Profiling and Area Averaging Methods

### 1.6.1 Height Parameters

*height function*, $Z(x,y)$ — the function used to represent the point-by-point deviations between the measured topography and the mean surface

*average roughness*, $AR_a$ — the arithmetic average of the absolute values of the measured height deviations from the mean surface taken within the evaluation area. Analytically, $AR_a$ is given in Cartesian coordinates by:

$$AR_a = (1/A_e) \int_0^{L_y} \int_0^{L_x} |Z(x,y)|\, dxdy$$

For a rectangular array of $M \times N$ digitized profile values $Z_{jk}$, the formula is given by:

$$AR_a = \frac{1}{MN} \sum_{k=1}^{M} \sum_{j=1}^{N} |Z_{jk}|$$

*root mean square (rms) roughness*, $AR_q$ — the root mean square average of the measured height deviations from the mean surface taken within the evaluation area. Analytically, $AR_q$ is given by:

$$AR_q = \left( (1/A_e) \int_0^{L_y} \int_0^{L_x} Z^2(x,y)\, dxdy \right)^{1/2}$$

The digital approximation is:

$$AR_q = \left[ \frac{1}{MN} \sum_{k=1}^{M} \sum_{j=1}^{N} Z_{jk}^2 \right]^{1/2}$$

*maximum area peak height*, $AR_p$ — the maximum height in the evaluation area with respect to the mean surface

*maximum area valley depth*, $AR_v$ — the absolute value of the minimum height in the evaluation area with respect to the mean surface

*area peak-to-valley height*, $AR_t$ — the vertical distance between the maximum height and the maximum depth in the evaluation area:

$$AR_t = AR_p + AR_v$$

NOTE: The height parameters are defined here with respect to the mean surface. One can use these definitions for characterization of either roughness and/or waviness parameters by choosing an appropriately filtered mean surface. For example, one could obtain the $AR_q$ for roughness by calculating a filtered, wavy mean surface with respect to which the heights $Z(x,y)$ are calculated. These heights would contain only roughness information and hence, the calculations of parameters based upon these heights would be estimates for roughness only.

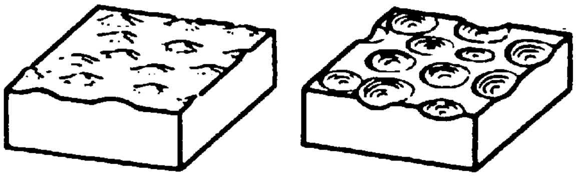


FIG. 1-21 AREA PEAKS (LEFT) AND AREA VALLEYS (RIGHT)



### 1.6.2 Waviness Parameters

*area waviness height*, $AW_t$ — the area peak-to-valley height of the filtered topography from which roughness and part form have been removed

### 1.6.3 Area Spacing Parameters

*directional peak spacing* — the distance between adjacent peaks in a profile through the surface topography that can be calculated in any selected direction over the measured surface (See Fig. 1-22.)

*area peak density* — the number of area peaks per unit area. Additional parameters can be defined that include the mean area peak spacing and parameters that count either area peaks, whose heights are above a selected reference surface, or area valleys, whose depths are below a selected reference surface.

### 1.6.4 Shape Parameters

*skewness*, $AR_{sk}$ — a measure of the asymmetry of surface heights about the mean surface. Analytically, $AR_{sk}$ may be calculated from:

$$AR_{sk} = \frac{1}{(AR_q)^3 A_e} \int_0^{L_y} \int_0^{L_x} Z^3(x,y)dxdy$$

For digitized profiles it may be calculated from:

$$AR_{sk} = \frac{1}{(AR_q)^3} \frac{1}{MN} \sum_{k=1}^{M} \sum_{j=1}^{N} Z_{jk}^3$$

*kurtosis*, $AR_{ku}$ — a measure of the peakedness of the surface heights about the mean surface. Analytically, $AR_{ku}$ may be calculated from:

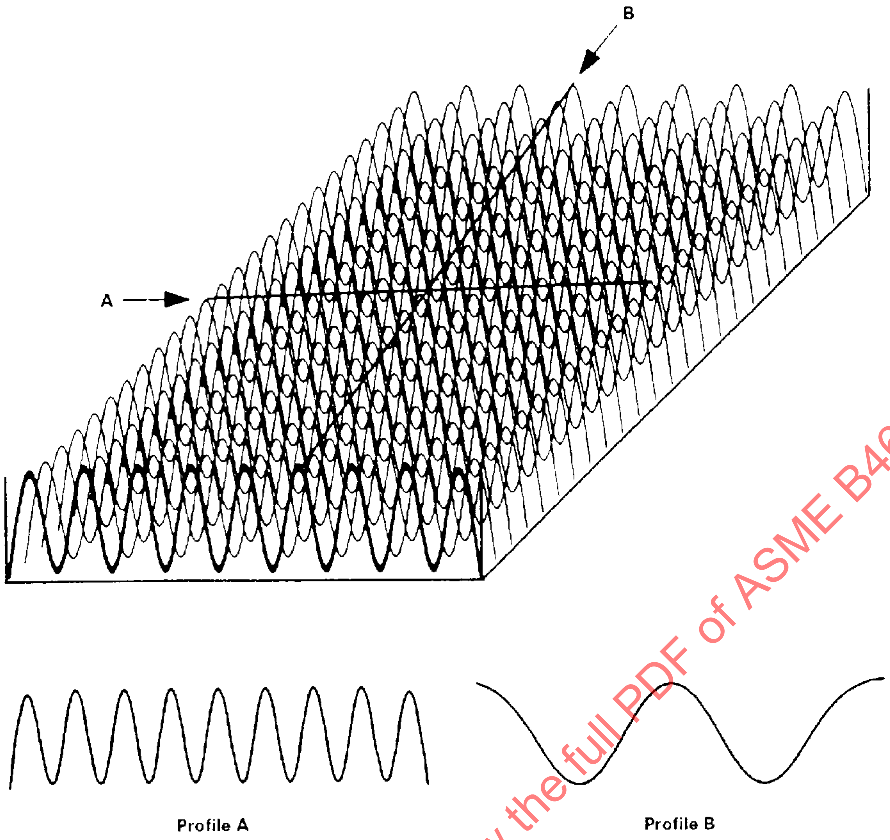



FIG. 1-22 COMPARISON OF PROFILES MEASURED IN TWO DIRECTIONS ON A UNIAXIAL, PERIODIC SURFACE SHOWING THE DIFFERENCE IN PEAK SPACING AS A FUNCTION OF DIRECTION



$$AR_{ku} = \frac{1}{(AR_q)^4 A_e} \int_0^{L_y} \int_0^{L_x} Z^4(x,y)dxdy$$

For a digitized profile, it may be calculated from:

$$AR_{ku} = \frac{1}{(AR_q)^4} \frac{1}{MN} \sum_{k=1}^{M} \sum_{j=1}^{N} Z_{jk}^4$$

NOTE: The calculated values of skewness and kurtosis are sensitive to outliers in the surface height data.

### 1.6.5 Other Parameters

*area average absolute slope*, $A\Delta_a$ — the arithmetic average of the absolute value of the derivative of the measured topography along a selected direction calculated over the sample area. For example, the direction can be selected to be perpendicular or parallel to the lay to provide information about the lay itself. Typically, instruments calculate this parameter in the $x$ or $y$ directions or in addition may take the square root of the sum of the squares of the $x$ and $y$ slopes.

*directional slopes*, $\Delta_a$ or $\Delta_q$ — parameters identical to the slope parameters of para. 1.4.4. Both the average absolute slope and the root mean square slope may be calculated in any direction for a single profile of the measured topography.

*area root mean square slope*, $A\Delta_q$ — the root mean square of the derivative of the measured topography along a selected direction calculated over the evaluation area. The modes of calculation in the $x$ or $y$ directions are the same as those for $A\Delta_a$.

*bearing area ratio* — the ratio of [the area of intersection of the measured topography with a selected surface parallel to the mean surface] to [the evaluation area]. By analogy with the *profile bearing length ratio* (see para. 1.4.3), this ratio is normally expressed as a percentage.

*area power spectral density function, APSD* — the square of the amplitude of the Fourier transform of the measured topography. This three-dimensional function is used to identify the nature of periodic features of the measured topography. Single profiles through the function can be used to evaluate lay characteristics. One version of the function is given by the following formula:

$$APSD(f_x, f_y) = \lim_{L_x, L_y \to \infty} \left(\frac{1}{L_x\, L_y}\right) \left| \int_{-L_y/2}^{L_y/2} \int_{-L_x/2}^{L_x/2} \cdot Z(x,y)\, e^{-i2\pi(f_x x + f_y y)}\, dxdy \right|^2$$

A digital approximation is given by:

$$APSD(f_x, f_y) = \frac{d_o^2}{MN} \left| \sum_{k=1}^{M} \sum_{j=1}^{N} Z_{jk}\, e^{-i2\pi[f_x(j-1)+f_y(k-1)]d_o} \right|^2$$

when the sampling interval here in both $x$ and $y$ directions is the same ($d_o$).

*area autocovariance function, AACV* — This three-dimensional function is used to determine the lateral scale of the dominant surface features present on the measured topography. Single profiles through the function can be used to evaluate lay characteristics. The function is equal to the inverse Fourier transform of the area power spectral density function but also may be estimated by the formula:

$$AACV(\tau_x, \tau_y) = \lim_{L_x, L_y \to \infty} \left(\frac{1}{L_x\, L_y}\right) \int_{-L_y/2}^{L_y/2} \int_{-L_x/2}^{L_x/2} \cdot Z(x,y)\, Z(x + \tau_x, y + \tau_y)\, dxdy$$

The digital approximation may be given by:

$$AACV(\tau_x, \tau_y) = \frac{1}{MN} \sum_{k=1}^{M-k'} \sum_{j=1}^{N-j'} Z_{jk}\, Z_{j+j',\, k+k'}$$

where

$\tau_x = j'd_o$
$\tau_y = k'd_o$

*area autocorrelation function, AACF* — the normalized area autocovariance function:

$$AACF(\tau_x, \tau_y) = AACV(\tau_x, t_y)/(AR_q)^2$$

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# SECTION 2 CLASSIFICATION OF INSTRUMENTS FOR SURFACE TEXTURE MEASUREMENT

## 2.1 Scope of Section 2

Instruments included in this Section are used for measurement of surface texture, which includes roughness and waviness. This classification is intended to aid in choosing and understanding these instruments and in determining which ASME B46.1 sections apply to their application. The classification system has been made as general as possible. However, instruments exist that do not clearly fit within any single instrument class. A schematic diagram of this classification with some examples is shown in Fig. 2-1.

## 2.2 Recommendation

In cases of disagreement regarding the interpretation of surface texture measurements, it is recommended that measurements with a Type I (skidless) instrument with Gaussian (50%) filtering be used as the basis for interpretation. The Type I instrument is listed below and the Gaussian filter is described in Section 9. The recommended bandwidth, stylus tip radius, and sampling interval are to be determined using Section 9, Table 9-2, based on the desired roughness cutoff ($\lambda_c$). The recommended maximum stylus force is given in Section 3, para. 3.3.5.2, given the desired tip radius.

The above recommendation does not apply if the surface structures to be assessed are outside the bandwidths of Section 9, Table 9-2, or if damage can occur to the surface when using the Type I instrument.

## 2.3 Classification Scheme

### 2.3.1 Type I: Profiling Contact Skidless Instruments

#### 2.3.1.1 Properties

(*a*) Measuring range often includes very smooth and rough surfaces;

(*b*) Measure roughness and may measure waviness and error of form with respect to an external datum;

(*c*) may have a selection of filters and parameters for data analysis;

(*d*) For stylus-type transducers, tips are often changeable and may range from submicrometer diamond styli to ball tips with radii of several millimeters;

(*e*) can generate filtered or unfiltered profiles;

(*f*) capable of either unfiltered profiling or topographical analysis (area profiling), or both.

#### 2.3.1.2 Examples

(*a*) skidless stylus-type adapted with LVDT (Linear Variable Differential Transformer) vertical measuring transducer;

(*b*) skidless stylus-type using an interferometric transducer;

(*c*) skidless stylus-type using a capacitance transducer.

#### 2.3.1.3 Reference

Section 3, Terminology and Measurement Procedures for Profiling, Contact, Skidless Instruments

### 2.3.2 Type II: Profiling Noncontact Instruments.

These techniques generally use an optical or electrical sensor.

#### 2.3.2.1 Properties

(*a*) capable of full profiling or topographical analysis or both;

(*b*) Noncontact feature may be advantageous for soft surfaces;

(*c*) Measurements may vary with sample material or reflectivity;

(*d*) These instruments may have difficulty measuring surface features with steep slopes;

(*e*) Selection of parameters and available filter types may vary with instrument techniques or defined data analysis;

(*f*) can generate filtered or unfiltered profiles.

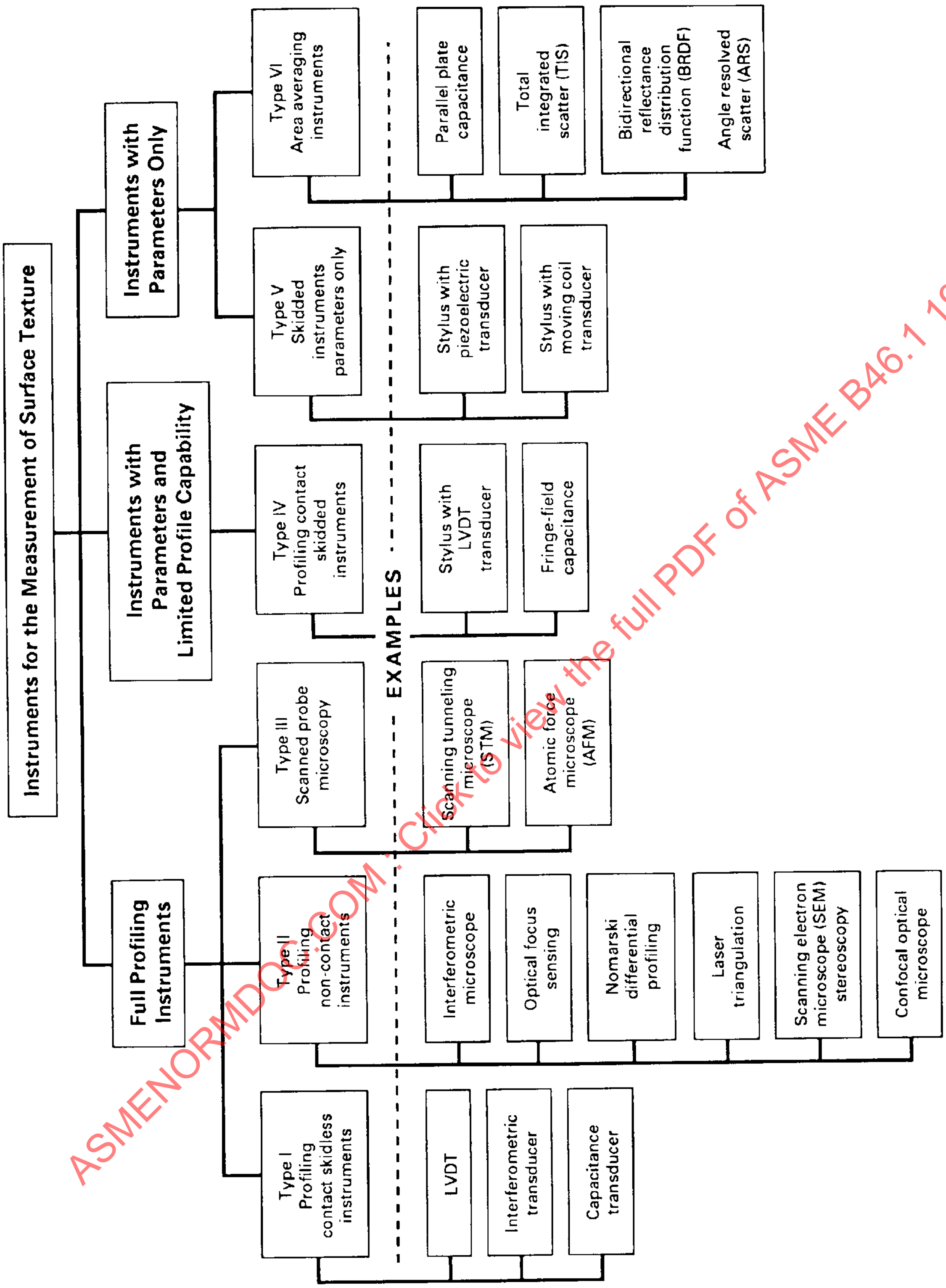


FIG. 2-1 CLASSIFICATION OF COMMON INSTRUMENTS FOR MEASUREMENT OF SURFACE TEXTURE

#### 2.3.2.2 Examples

(*a*) interferometric microscope
(*b*) optical focus sensing
(*c*) Nomarski differential profiling
(*d*) laser triangulation
(*e*) scanning electron microscope (SEM) stereoscopy
(*f*) confocal optical microscope

#### 2.3.2.3 References

Section 5, Measurement Techniques for Area Profiling

Appendix C, A Review of Additional Surface Measurement Methods

### 2.3.3 Type III: Scanned Probe Microscopes

#### 2.3.3.1 Properties

(*a*) high spatial resolution instruments (at or near atomic scale);
(*b*) Measurement areas may be limited.

#### 2.3.3.2 Examples

(*a*) scanning tunneling microscope (STM)
(*b*) atomic force microscope (AFM)

#### 2.3.3.3 Reference

Section 5, Measurement Techniques for Area Profiling

### 2.3.4 Type IV: Profiling Contact Skidded Instruments

#### 2.3.4.1 Properties

(*a*) Use a skid as a datum, usually in order to eliminate longer spatial wavelengths. Therefore, waviness and error of form cannot be measured with this type of instrument;
(*b*) may have a selection of filters and parameters for data analysis;
(*c*) For stylus-type tranducers, the tip radius is commonly 10 $\mu$m or less. With a 10 $\mu$m stylus radius, the instrument may not be suitable for measuring very short spatial wavelengths;
(*d*) This type of instrument yields surface parameter values and generates an output recording of filtered or skid-modified profiles.

#### 2.3.4.2 Examples

(*a*) skidded, stylus-type with LVDT vertical measuring transducer
(*b*) fringe-field capacitance (FFC) transducer

#### 2.3.4.3 Reference

Section 4, Measurement Procedures for Contact, Skidded Instruments

### 2.3.5 Type V: Skidded Instruments With Parameters Only

#### 2.3.5.1 Properties

(*a*) Use a skid as a datum, usually in order to eliminate longer spatial wavelengths. Therefore, waviness and error of form cannot be measured with this type of instrument;
(*b*) Filters are typically of the 2RC type;
(*c*) typically produce measurements of the $R_a$ parameter, but other parameters may also be available;
(*d*) For those instruments using a diamond stylus, the stylus tip radius is commonly 10 $\mu$m but may be smaller. With a 10 $\mu$m stylus radius, these instruments may not be suitable for measuring very short spatial wavelengths;
(*e*) This type of instrument does not generate a profile.

#### 2.3.5.2 Examples

(*a*) skidded, stylus-type with piezoelectric measuring transducer
(*b*) skidded, stylus-type with moving coil measuring transducer

#### 2.3.5.3 Reference

Section 4, Measurement Procedures for Contact, Skidded Instruments

### 2.3.6 Type VI: Area Averaging Methods

#### 2.3.6.1 Properties

(*a*) These instruments measure averaged parameters over defined areas;
(*b*) Profiles are not available from these instruments.

#### 2.3.6.2 Examples

(*a*) parallel plate capacitance (PPC) method
(*b*) total integrated scatter (TIS)
(*c*) angle resolved scatter (ARS)/bidirectional reflectance distribution function (BRDF)

#### 2.3.6.3 Reference

Section 6, Measurement Techniques for Area Averaging

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## SECTION 3 TERMINOLOGY AND MEASUREMENT PROCEDURES FOR PROFILING, CONTACT, SKIDLESS INSTRUMENTS

### 3.1 Scope of Section 3

This Section defines terminology and measurement procedures for Type I, profiling, contact, skidless instruments, per Section 2. It addresses terminology, calibration, and use of these instruments for the assessment of individual surface profiles. In addition, a description of the Type I instrument that complies with ISO 3274 is also included. In cases of disagreement regarding the interpretation of surface texture measurements, a Type I instrument in compliance with ISO 3274 should be used. This recommendation is also discussed in Section 2. Other types of instruments may be used, but the correlation of their measurements with those of Type I instruments that comply with this Section must be demonstrated.

### 3.2 References

Section 1, Terms Related to Surface Texture

Section 2, Classification of Instruments for Surface Texture Measurement

ISO 3274:1975, Instruments for the Measurement of Surface Roughness by the Profile Method — Contact (Stylus) Instruments of Consecutive Profile Transformation — Contact Profile Meters, System M

ISO 4288, Rules and Procedures for the Measurement of Surface Roughness using Stylus Instruments

### 3.3 Terminology

**3.3.1 Profiling, Contact, Skidless Instrument.** A profiling, contact, skidless instrument is an instrument which measures displacements of a stylus relative to an external datum. This stylus is traversed over the surface of interest. The displacements of the stylus are linearly proportional to the heights of features contained on the surface. The measured stylus displacements yield the measured surface profile.

**3.3.2 Measuring Loop.** The measuring loop comprises all components which connect the instrument stylus to the workpiece surface. This loop can consist of (but is not necessarily restricted to) the workpiece, fixturing, measuring stand, traverse unit, and stylus pickup (see para. 3.3.5). Ideally, the number of components in the measuring loop should be minimized. This minimization generally reduces the system sensitivity to vibration and thermal effects.

**3.3.3 Profile Coordinate System.** The profile coordinate system is that right-handed, three-dimensional, Cartesian coordinate system defined by the work surface and the direction of motion of the stylus. In this system, the stylus traverse defines the $x$ axis and the displacements normal to the work surface define the $z$ axis (see Fig. 3-1).

**3.3.4 Stylus.** The stylus is the finite object which contacts the workpiece surface to be assessed.

**3.3.4.1 Stylus Tip.** The stylus tip is critical in surface profile assessment as it determines the size and shape of surface features which can be properly assessed. Refer to Section 9 for stylus tip size selection when the short wavelength cutoff is specified. Basic tip geometries are described below.

**3.3.4.2 Conical Stylus With Spherical Tip.** The conical stylus shall incorporate an included angle ($\alpha$) of 60 deg or 90 deg (see Fig. 3-2). The effective radius ($r$) of the tip shall be 2, 5, or 10 $\mu$m (0.00008, 0.0002, or 0.0004 in.) A definition of effective radius is given in Section 4.

**3.3.4.3 Truncated Pyramid Tip.** A truncated pyramid stylus can also be used with a rectangular contact area 2–4 $\mu$m (0.00008-0.00016 in.) on a side ($a$ or $b$ in Fig. 3-3) and an included angle ($\alpha$) (in the direction of traverse) of 60 deg or 90 deg.

**3.3.4.4 Stylus Generated Profile.** The stylus generated profile is that profile which is generated by the finite stylus tip as it is traversed relative to

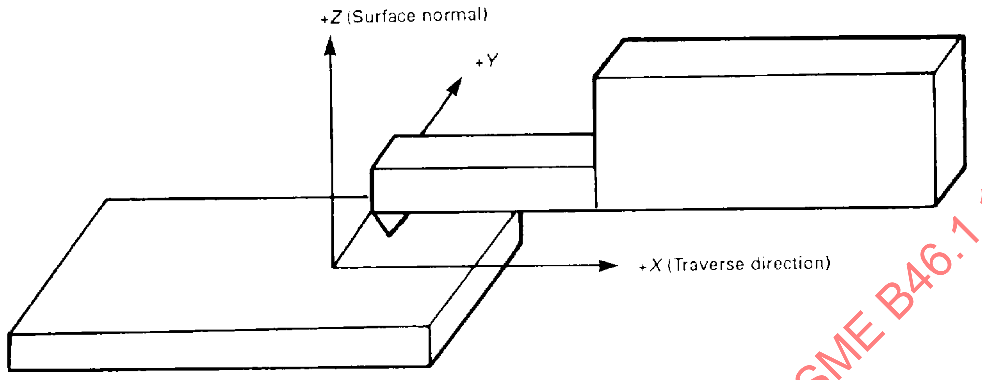



FIG. 3-1 PROFILE COORDINATE SYSTEM

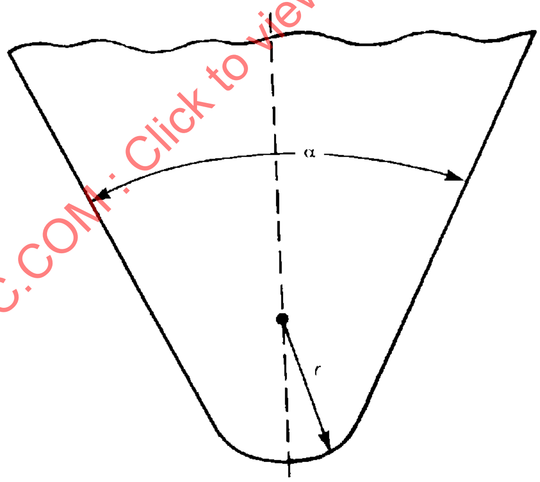



FIG. 3-2 CONICAL STYLUS TIP

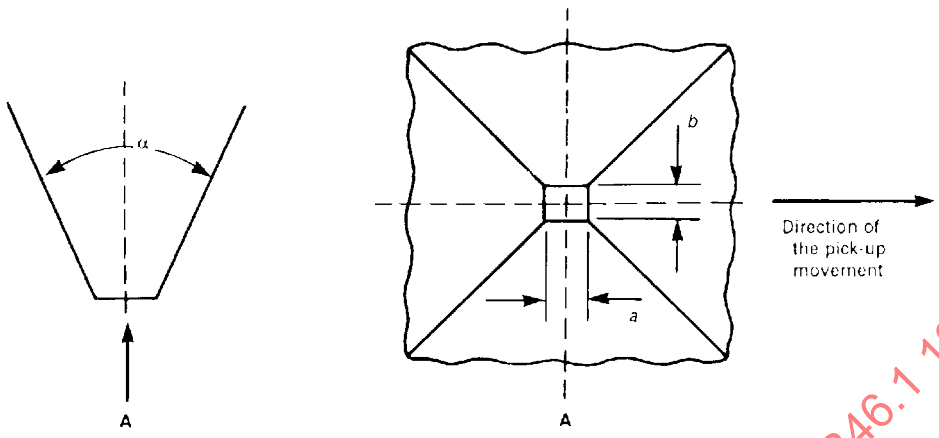



FIG. 3-3 TRUNCATED PYRAMID TIP



the workpiece surface. This profile is not necessarily the actual cross section of the workpiece surface as some surface features of the surface may be inaccessible for given stylus dimensions.

**3.3.5 Pickup.** The pickup comprises the stylus, stylus holding mechanism, measuring transducer, and any signal conditioning associated with the measuring transducer. As this system is traversed across the workpiece, $z$ axis displacements of the stylus are transmitted to the measuring transducer, thus generating a profile of displacements relative to the reference datum.

**3.3.5.1 Static Measuring Force.** The static measuring force is the force, in the $z$ direction, exerted into the workpiece surface by the stylus while the stylus is at rest. When specifying an instrument, the static measuring force is given at the midpoint of the $z$ range of the instrument.

**3.3.5.2 Maximum Recommended Static Measuring Force.** The maximum recommended values of static measuring force are determined by the stylus radius. For the truncated pyramid, use the smaller of the dimensions of the truncated flat as the nominal tip radius.

| Nominal Tip Radius | Maximum Recommended Static Measuring Force at Mean Position of Stylus, $N$ (gf) |
|---|---|
| 2 $\mu$m (0.00008 in.) | 0.0007 (0.07) |
| 5 $\mu$m (0.0002 in.) | 0.004 (0.4) |
| 10 $\mu$m (0.0004 in.) | 0.016 (1.6) |

**3.3.5.3 Static Measuring Force Variation.** The change in static measuring force in the $z$ direction over the entire $z$ measuring range of the pickup.

**3.3.5.4 Dynamic Measuring Force.** The dynamic measuring force is the instantaneous normal force associated with the motion of the stylus as it is traversed relative to the surface. This force may be difficult to quantify and varies both with stylus location on the surface and with the speed of the traverse.

**3.3.5.5 Total Stylus Force.** The total stylus force is that instantaneous force resulting from the combination of static and dynamic normal forces during measurement.

**3.3.5.6 Pickup Transmission Characteristic.** This function indicates the percentage of the amplitude of a sinusoidal surface profile transmitted by the pickup as a function of surface spatial wavelength (see Section 9).

**3.3.5.7 Pickup Measuring Range.** The pickup measuring range is the $z$ axis range over which the surface profile heights can be properly assessed by the pickup.

**3.3.5.8 Pickup Measuring Resolution.** The pickup measuring resolution is the smallest $z$ profile height increment detectable by the pickup. Often, this is a function of the magnification selection and should be reported for each available magnification.

**3.3.5.9 Pickup Range-to-Resolution Ratio.** The pickup range-to-resolution ratio is the ratio of total $z$ axis measuring range to the pickup measuring resolution at a given magnification.

**3.3.5.10 Pickup Nonlinearity.** The pickup nonlinearity is the deviation in $z$ axis magnification as a function of stylus vertical displacement.

**3.3.5.11 Pickup Hysteresis.** The hysteresis of a pickup is the difference in the measured stylus position for upward versus downward stylus motion.

**3.3.6 Drive Unit.** The drive unit provides $x$ axis range and motion control. This motion determines the instantaneous $x$ axis positions for corresponding $z$ axis positions. The drive unit also controls the speed of traverse.

**3.3.6.1 Reference Guide.** The reference guide determines the plane of the measured profile through the linear guidance of the stylus drive unit during the traverse. In a typical application, where the stylus measures height displacements in the $z$ direction, the reference guide constrains the drive unit in the $y$ and $z$ directions.

**3.3.6.2 *x* Axis Straightness.** The $x$ axis straightness is the measure of departure of the reference guide from a straight line in both the $y$ and $z$ directions. It can be computed as the distance between two parallel lines in the direction under assessment ($y$ or $z$) whereby the two lines completely enclose the data generated by the reference guide and have minimum separation.

**3.3.6.3 *x* Axis Range.** The $x$ axis range is that maximum length in the direction of traverse over which a profile measurement can be made.

**3.3.6.4 *x* Axis Resolution.** The $x$ axis resolution is defined as the smallest increment in the $x$ direction which can be resolved. The $x$ axis position can be determined either by a velocity-time system or by an encoding system.

**3.3.6.5 External Datum.** The external datum is the reference with respect to which stylus displacements are measured. This datum may be separate from the reference guide or integral with it.

**3.3.7 Amplifier.** The amplifier magnifies the signal generated by the pickup.

**3.3.7.1 Amplifier Gain.** The amplifier gain is the amount of $z$ magnification provided by the amplifier. A selection of gain settings is available on many instruments.

**3.3.8 Analog-to-Digital Conversion.** This Section, covering analog to digital conversion, is optional for Type I instruments according to the classification scheme of Section 2, which covers both analog and digital instruments. However, this Section covers terminology associated with the digitization and storage of profile data which is a requirement if an instrument is to comply with ISO 3274.

**3.3.8.1 Analog-to-Digital Converter.** The analog-to-digital converter (ADC) converts the analog $z$ signal to discrete, digital values. These values, together with the sampling rate and stylus traverse speed, or $x$ axis encoder reading, make up the digital representation of the traversed profile.

**3.3.8.2 Nyquist Wavelength.** The Nyquist wavelength is the shortest detectable wavelength for a given sampling rate. This wavelength is computed as twice the $x$ axis spacing of the digital values (the sampling interval). It should be noted that in practical terms, the measured amplitude of a sinusoidal profile at this wavelength may be smaller than its actual amplitude because of the phase difference between the sampled data points and the profile peaks and valleys. Refer to Section 9 for further information pertaining to sampling interval.

**3.3.8.3 Aliasing.** When analog data containing wavelengths shorter than the Nyquist wavelength are sampled, these wavelengths will be falsely represented as wavelengths longer than the Nyquist wave-

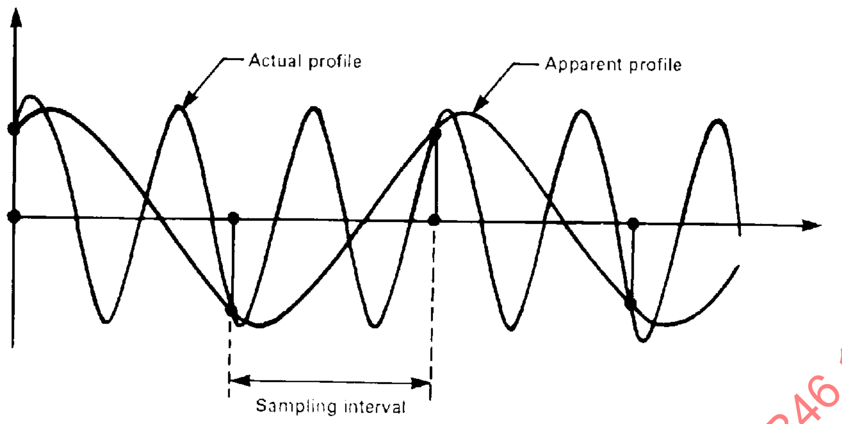



**FIG. 3-4 ALIASING**

length. This phenomenon is referred to as aliasing and is depicted in Fig. 3-4.

**3.3.8.4 Antialiasing Filter.** The antialiasing filter removes wavelengths shorter than the Nyquist wavelength prior to digitization. This eliminates the potential for aliasing. This filtering can be the result of mechanical filtering due to the finite stylus tip or the result of an electronic filter typically incorporated in the analog-to-digital converter.

**3.3.9 Primary Measured Profile.** The primary measured profile is the complete representation of the measured workpiece surface after application of a short wavelength filter to eliminate high frequency noise or artifacts (see Section 9).

**3.3.10 Instrument Sinusoidal Transmission Function.** The instrument sinusoidal transmission function describes the percentage of transmitted amplitude for sine waves of various wavelengths at given tracing speeds as represented in the analog or digital signal prior to filtering. This transmission function describes the combined mechanical and electronic effects of the instrument on the stylus generated profile.

**3.3.11 Instrument Nonlinearity.** The instrument nonlinearity is the deviation in measured $z$ axis displacement as a function of the actual $z$ axis stylus displacement.

**3.3.12 Instrument Measuring Range.** The instrument measuring range is the $z$ axis range over which the surface profile heights can be properly assessed by the instrument.

**3.3.13 Instrument Measuring Resolution.** The instrument measuring resolution is the smallest detectable $z$ profile height increment. Often, this is a function of the magnification and should be reported for each available magnification.

**3.3.14 Instrument Range-to-Resolution Ratio.** The instrument range-to-resolution ratio is the ratio of total $z$ axis measuring range to the instrument measuring resolution at a given magnification.

**3.3.15 Zero Point Drift.** The zero point drift is the recorded change in $z$ reading under conditions where the stylus is held stationary at constant ambient temperature and where outside mechanical influences are minimal.

**3.3.16 Residual Profile.** The residual profile is that profile which is generated by internal and external mechanical disturbances as well as by devia-

**TABLE 3-1 CUTOFF VALUES FOR PERIODIC PROFILES USING $S_m$**

| $S_m$ | | | | Cutoff Length [Note (1)] | | Evaluation Length | |
|---|---|---|---|---|---|---|---|
| Over | | Up to (Including) | | | | | |
| mm | (×0.001 in.) | mm | (×0.001 in.) | mm | (in.) | mm | (in.) |
| 0.013 | (0.5) | 0.04 | (1.6) | 0.08 | (0.003) | 0.40 | (0.016) |
| 0.040 | (1.6) | 0.13 | (5) | 0.25 | (0.010) | 1.25 | (0.05) |
| 0.13 | (5) | 0.40 | (16) | 0.80 | (0.03) | 4.0 | (0.16) |
| 0.40 | (16) | 1.3 | (50) | 2.5 | (0.10) | 12.5 | (0.5) |
| 1.3 | (50) | 4.0 | (160) | 8.0 | (0.3) | 40.0 | (1.6) |

NOTE:
(1) For calibration specimens the recommended cutoffs are given in Section 11.

tions in the reference guide and datum when an ideally smooth surface is measured by an instrument.

**3.3.17 *x* Axis Profile Component Deviations.** The *x* axis profile component deviations are those deviations between the actual profile and the measured profile in the *x* direction.

**3.3.18 Short-Wave Transmission Limit.** The short-wave transmission limit is the short wavelength boundary of the band of wavelengths included in the desired profile (for example, the roughness profile). Ideally, this boundary is obtained via analog or digital filtering whereby short wavelengths are attenuated in amplitude (see also Section 9).

**3.3.19 Profile Filter.** The profile filter is the filter which separates the roughness ($R$) from the waviness ($W$) and form error ($F$) components of the primary profile ($P$). This filter consists of either an analog or a digital implementation of a 2RC or a Gaussian filter. Based on sine wave amplitude transmission characteristics and compliance with ISO standards, use of the digital Gaussian filter is recommended. For further discussion of profile filtering, refer to Section 9.

**3.3.20 Profile Filter Cutoff Selection.** Filter cutoff length is determined in part by the $x$ and $z$ aspects of the surface under evaluation. Guidelines are given below for periodic and nonperiodic profiles based on estimates of $S_m$ and $R_a$, respectively. For the measurement process where no specification exists, care must be taken to choose a cutoff value that includes all of the surface irregularities to be evaluated.

**3.3.20.1 Profile Filter Cutoff Selection For Periodic Profiles**

(*a*) Estimate the surface roughness parameter $S_m$ graphically from an unfiltered profile trace.

(*b*) Determine the recommended cutoff value from the estimated or measured $S_m$ value from Table 3-1.

**3.3.20.2 Profile Filter Cutoff Selection For Nonperiodic Profiles**

(*a*) Estimate the roughness parameter, $R_a$, for the surface profile to be measured.

(*b*) Use Table 3-2 to estimate the cutoff length for the estimated $R_a$ value.

(*c*) Measure the $R_a$ value of the profile at the estimated cutoff.

(*d*) If the measured $R_a$ is outside the range of values for the estimated cutoff length, adjust the cutoff accordingly. Repeat the measurement and cutoff adjustment until an acceptable combination is reached.

(*e*) If the next cutoff length shorter than the acceptable one has not been tested, measure $R_a$ at this shorter cutoff length. If this shorter cutoff length is acceptable in terms of the resultant $R_a$, then this becomes the measurement cutoff. If this new cutoff length and $R_a$ combination do not conform to Table 3-2, then the cutoff length determined in (d) above should be used.

**3.3.21 Profile Recording and Display.** After filtering, the measured profile is typically plotted on a graph for visual interpretation. Digital instruments can also store the discrete data points for further numerical analysis and graphical display.

**TABLE 3-2 CUTOFF VALUES FOR NONPERIODIC PROFILES USING $R_a$**

| $R_a$ Over | | Up to (Including) | | Cutoff Length | | Evaluation Length | |
|---|---|---|---|---|---|---|---|
| μm | (μin.) | μm | (μin.) | mm | (in.) | mm | (in.) |
| — | — | 0.02 | (0.8) | 0.08 | (0.003) | 0.40 | (0.016) |
| 0.02 | (0.8) | 0.10 | (4) | 0.25 | (0.010) | 1.25 | (0.05) |
| 0.10 | (4) | 2.0 | (80) | 0.80 | (0.03) | 4.0 | (0.16) |
| 2.0 | (80) | 10 | (400) | 2.5 | (0.10) | 12.5 | (0.5) |
| 10 | (400) | — | — | 8.0 | (0.3) | 40 | (1.6) |

**3.3.21.1 *z* Axis Magnification.** The $z$ axis magnification is the ratio of the displayed profile heights to the actual heights of the corresponding surface features on the workpiece. This magnification may also be represented as a surface $z$ displacement (in units of length) per scale division on a graph.

**3.3.21.2 *x* Axis Magnification.** The $x$ axis magnification is the ratio of the length of the displayed profile to the actual length traversed by the stylus. This magnification can also be represented as surface displacement (in units of length) per scale division on a graph.

**3.3.21.3 Magnification Ratio (Aspect Ratio).** The magnification ratio or aspect ratio is the ratio of the $z$ magnification to the $x$ magnification.

**3.3.22 Profile Evaluation.** The evaluation of the primary roughness and waviness profiles shall be by the definitions and formulas given in Section 1.

## 3.4 Measurement Procedure

The following paragraphs provide guidelines for the use of Type I instruments in the measurement of workpiece surfaces.

**3.4.1 Stylus Inspection.** The instrument's stylus should be inspected for cleanliness, wear, and mechanical damage as per the following procedure.

**3.4.1.1 Visual Inspection.** Prior to its use, the stylus should be visually inspected for cleanliness and mechanical integrity. If the stylus tip is loose, the shaft is bent, or if the mounting surfaces (for a detachable stylus) appear to have excessive wear, the stylus should be repaired or replaced. The stylus must also be clean and free from any lint or residual film left from the cleaning process.

**3.4.1.2 Magnified Inspection.** The stylus tip should also be inspected with the aid of a magnification device (for example, a microscope or optical comparator). Once again, a broken or worn stylus should be repaired or replaced. See also Section 11 for procedures to evaluate the stylus tip.

**3.4.2 Instrument Calibration.** The instrument should be calibrated according to the instrument manufacturer's specifications using a precision reference specimen (see Section 11) traceable to NIST. This specimen should also be clean and free from signs of wear which may affect the calibration of the instrument.

**3.4.3 Workpiece Cleanliness.** The workpiece to be assessed should be cleaned with a nondamaging solvent and is to be free from any residual film or other debris prior to measurement.

**3.4.4 Workpiece Fixturing.** A visual assessment of the workpiece surface should be made to determine a representative portion of the surface on which the trace is to be made. The workpiece should then be securely fixtured relative to the instrument stylus and traverse direction such that the lay of the surface, if any, is perpendicular to the direction of traverse.

**3.4.5 Instrument/Workpiece Leveling and Alignment.** The instrument and workpiece should be aligned such that the underlying geometry of the surface under test and its relationship to the traverse minimize total stylus displacement during measurement over the evaluation length. For flat surfaces, this requires that the surface under test be levelled relative to the instrument traverse unit. Commonly, the measuring instrument is adjusted for tilt relative to the workpiece until no significant relative tilt is detected by the stylus as it is traversed. For cylindrical components, in addition to leveling, the axis of the component should be closely aligned with the axis of the traverse to avoid the presence of a curvature in the trace.

**3.4.6 Assessment of the Workpiece Surface.** Upon fulfilling the above requirements, the stylus may be positioned and the measurement made. If a parameter measurement is required, for example the roughness parameter $R_a$, the value can be obtained after proper filtering.

## SECTION 4 MEASUREMENT PROCEDURES FOR CONTACT, SKIDDED INSTRUMENTS

### 4.1 Scope of Section 4

**4.1.1 General.** Contact, skidded instruments and procedures used to determine roughness values of a given surface shall comply with the specifications in this Section. The use of other principles of surface roughness measurement are explained in other sections of this Standard.

**4.1.2 Types IV and V Instruments.** Many instruments for measuring surface roughness depend on electrical processing of the signal produced by the vertical motion of a contacting probe traversed along the surface, in general, perpendicular to the lay direction. A convenient means of providing a reference surface for measuring probe movement is to support the tracer containing the probe on *skids* whose radii are large compared to the height and spacing of the irregularities being measured.

This Section is concerned only with such tracer type instruments using skidded, contact probes (see Fig. 4-1). In the case of the stylus, both the skid and stylus contact the surface. In the case of the fringe-field capacitance (FFC) probe, the skid contacts the surface but the sensor does not. These instruments are classified as Type IV or Type V in Section 2.

### 4.2 References

Section 1, Terms Related to Surface Texture

Section 2, Classification of Instruments for Surface Texture Measurement

Section 3, Terminology and Measurement Procedures for Profiling, Contact, Skidless Instruments

Section 9, Filtering of Surface Profiles

Section 11, Specifications and Procedures for Precision Reference Specimens

ASME Y14.36M, Surface Texture Symbols

### 4.3 Purpose

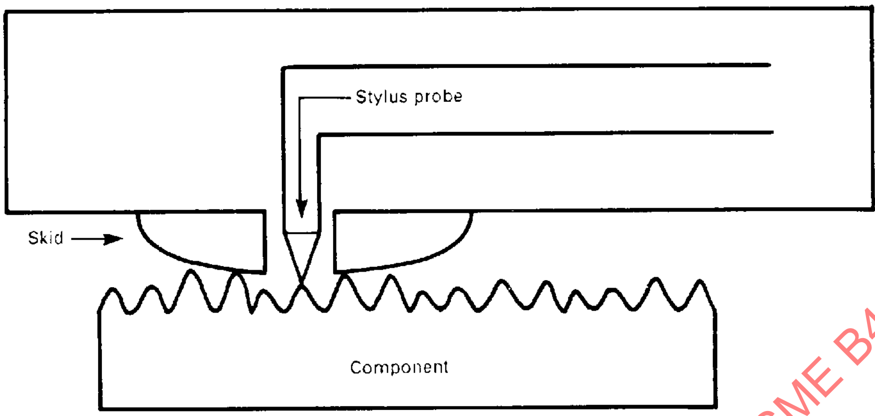
The purpose of this Section is to foster the uniformity of surface roughness evaluation among contact, skidded instruments and to allow the specification of desired surface texture values with assurance of securing repeatable results. Special configurations of instruments for special purposes such as small radius skids, long styli, fast response, and special cutoff characteristics do not meet the requirements of this Section but are useful for comparative purposes. The instrument manufacturer shall supply information where deviations exist.

### 4.4 Instrumentation

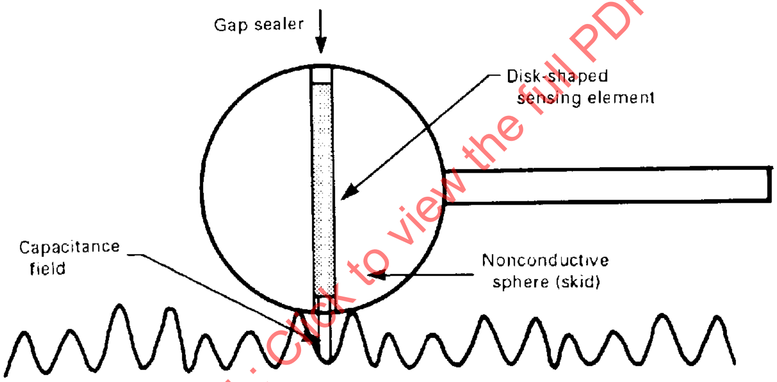
**4.4.1 Roughness Average Value $R_a$ from Averaging and Digital Readout Instruments**

(*a*) The readout device shall display the average deviation from the filtered mean line in $\mu$m ($\mu$in.). This quantity is the roughness average $R_a$, formerly known as arithmetic average (AA) and centerline average (CLA) and is explained in further detail in Section 1. The filtered mean line is also described in Section 1.

(*b*) For uniform interpretation of readings from contact type instruments of the averaging type, it should be understood that the reading which is considered significant is the mean reading around which the value tends to dwell or fluctuate with a small amplitude. Analog meters are damped to minimize acute deflections; nevertheless, extremely high and low momentary readings often occur. These anomalous readings are not representative of the average surface condition, and such readings should not be used in determining roughness average. An instrument with a digital readout integrates these high and low momentary readings and displays the surface roughness averaged over a significant length of surface profile.




(a) Stylus Probe




(b) Typical Fringe-Field Capacitance Probe

GENERAL NOTES:
(a) The fringe-field capacitance (FFC) probe is comprised of a conductive thin film sensor embedded in a non-conductive sphere. The sensor is concentric with the equator of the sphere, but is uniformly offset from the sphere edge.
(b) This Fig. is not drawn to scale; the skid radius is shown smaller than it is in reality, and the roughness structure is shown larger in comparison with the probe assembly than it is in reality.

**FIG. 4-1 SCHEMATIC DIAGRAMS OF A TYPICAL STYLUS PROBE AND FRINGE-FIELD CAPACITANCE PROBE**

**4.4.2 Cutoff Selection.** In all cases, the cutoff must be specified on drawings created or revised after this Standard is published. On prior drawings when the cutoff is not specified, the 0.8 mm (0.03 in.) value is assumed. The set of recommended cutoff values is given in Tables 4-1 and 4-2. See Section 3 for cutoff selection guidelines. See Section 9 for details of the filtering techniques. The effect of the variation in cutoff is illustrated in Fig. 4-2.

**4.4.3 Response Time.** For instruments with analog meter readout, the response time, defined as the time to attain 95% of the final reading, shall be no shorter than 0.5 sec or $10/f_c$ sec, whichever is the longer period, where the frequency $f_c$ (in hertz) corresponds to the long wavelength cutoff at the traversing speed $v$, i.e., $f_c = v/\lambda_c$.

**4.4.4 Traversing Length.** To provide full readings with the response times specified in para. 4.4.3 for averaging type instruments using analog meter readouts, the traversing length used for any measurement shall be compatible with the selected cutoff in accordance with Table 4-1.

When these analog readout instruments are used, the traversing length need not be continuous in one direction, provided the time required to reverse the direction of trace is short compared to the time the tracer is in motion. In addition, surfaces must be large enough to permit a minimum travel in one direction of five times the cutoff. Otherwise, the readings may not be representative of the actual roughness of a surface but may be useful for comparative purposes. Under these conditions, the use of other types of instruments may provide additional useful information about the surface condition.

**4.4.5 Stylus Probe**

**4.4.5.1 Stylus Tip Radius.** Stylus dimensions limit the size of the irregularities that may be detected in a measurement. For all measuring instruments, a nominal 10 $\mu$m (400 $\mu$in.) effective (spherical) tip radius shall be assumed unless otherwise specified. Effective radius here is defined as the average radius of two concentric and minimally separated circles whose centers fall on the conical flank angle bisector and whose arcs are limited by radial lines drawn 45 deg either side of this bisector. The arcs and the radii must contain the stylus tip profile.

The tip radius of a new stylus shall be within ±30% of the nominal value. The tip radius of a used in-service stylus shall be within ±50% of the nominal value. This can be evaluated as shown in Fig. 11-7 of Section 11. Since styli of small radius are subject to wear and mechanical damage even when made of diamond, it is recommended that frequent checks of the stylus be made to ensure that the tip radius does not exceed the specified value. Changes in stylus condition may be checked by several methods discussed in Section 11.

Other stylus radii may be used where the 10 $\mu$m (400 $\mu$in.) radius does not provide the information desired. Recommended standard sizes are 10 $\mu$m (400 $\mu$in.), 5 $\mu$m (200 $\mu$in.), and 2 $\mu$m (80 $\mu$in.).

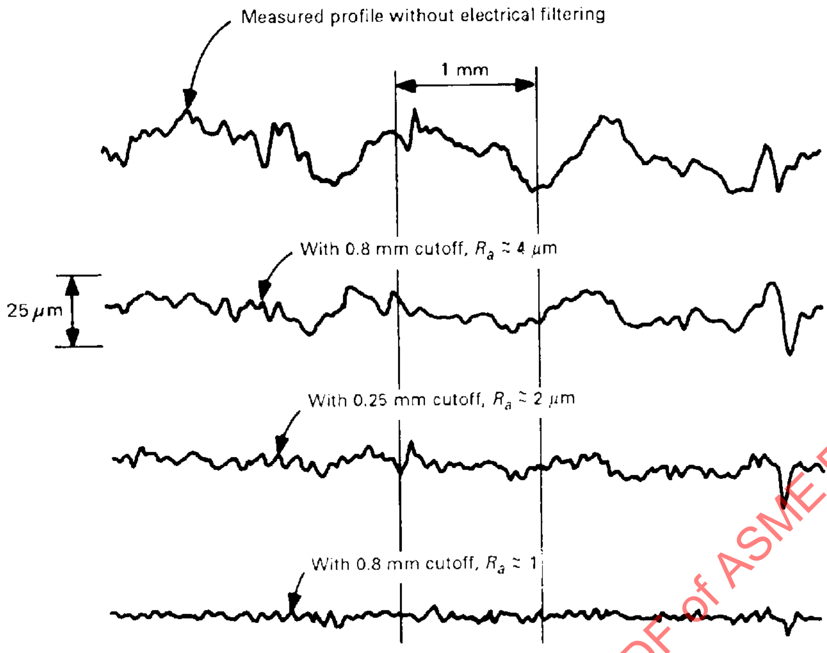
**4.4.5.2 Stylus Shape.** The cone-shaped stylus with a nominally spherical tip shall be considered standard unless otherwise specified. The use of a chisel point or a knife edge stylus, where desired, must be specified (see Section 3).

**TABLE 4-1 MEASUREMENT CUTOFFS AND TRAVERSING LENGTHS FOR CONTINUOUSLY AVERAGING INSTRUMENTS USING ANALOG METER READOUTS**

| Cutoff | | Measurement Traversing Length | |
|---|---|---|---|
| mm | (in.) | mm | (in.) |
| 0.08 | 0.003 | 1.5–5 | 0.06–0.2 |
| 0.25 | 0.01 | 5–15 | 0.2–0.6 |
| 0.8 | 0.03 | 15–50 | 0.6–2.0 |
| 2.5 | 0.10 | 50–150 | 2.0–6.0 |
| 8.0 | 0.3 | 150–500 | 6.0–20 |

**TABLE 4-2 MEASUREMENT CUTOFFS AND MINIMUM EVALUATION LENGTHS FOR INSTRUMENTS MEASURING INTEGRATED ROUGHNESS VALUES OVER A FIXED EVALUATION LENGTH**

| Cutoff | | Minimum Evaluation Length | |
|---|---|---|---|
| mm | (in.) | mm | (in.) |
| 0.08 | 0.003 | 0.4 | 0.016 |
| 0.25 | 0.01 | 1.25 | 0.05 |
| 0.8 | 0.03 | 4.0 | 0.16 |
| 2.5 | 0.10 | 7.5 | 0.3 |
| 8.0 | 0.30 | 24 | 0.9 |




GENERAL NOTE: Profiles have unequal vertical and horizontal magnification.

**FIG. 4-2 EFFECTS OF VARIOUS CUTOFF VALUES**

**4.4.5.3 Stylus Force (for Stylus Instruments).** To ensure that the stylus accurately follows the contour of the surface being measured, a force is required to push it against the surface. If this force is too large, the stylus will plow through the surface irregularities instead of following their profile.

For the standard tip radius of 10 $\mu$m (400 $\mu$in.), the maximum stylus force shall be 0.016 $N$ (1.6 gf), as determined according to Section 3.

The minimum stylus force shall be sufficient to maintain contact with the surface under conditions of maximum irregularity amplitude, maximum tracing speed, and minimum spatial wavelength for which the instrument is designed.

On soft materials, the stylus may make a visible mark as it is being used. Such a mark does not necessarily mean that the measurement is incorrect. In fact, in many cases the mark may have been made by the skid supporting the probe. In some cases, it may be desirable to make supplementary measurements by other means to ascertain that the penetration of the stylus into the material is small compared to the dimensions of the irregularities being measured.

**4.4.5.4 Stylus Probe Supports (Skids)**

(*a*) If a single skid is employed to provide a reference surface, it shall preferably have a radius of curvature in the direction of the trace of at least 50 times the cutoff. If two skids transverse to the probe are used, their radius of curvature shall be not less than 9 times the cutoff.

(*b*) The skids and the probe shall be in line either in the direction of motion or perpendicular to the direction of motion. In some acceptable designs, the skid is actually concentric with the probe. The arrangement of skids, or external reference guides (see Section 3) if no skids are used, shall be such as to constrain the probe to move parallel to the nominal surface being measured. The probe support shall be such that under normal operating conditions no lateral deflections sufficient to cause error in the roughness measurement will occur.

(*c*) If it is necessary to use skid radii smaller than standard, the long wavelength response of the instrument may be affected. Skids normally supplied with conventional stylus-type instruments often have too small a radius to provide accurate readings on surfaces rougher than 12.5 $\mu$m (500 $\mu$in.) $R_a$. For measurements with cutoff values of 25 mm (1 in.) or more, it is generally preferable to use an external reference surface rather than a skid.

#### 4.4.6 Fringe-Field Capacitance (FFC) Probe

**4.4.6.1 Probe Tip Radius.** The FFC probe does not mechanically track the surface like a stylus instrument; however, there is a lateral spatial resolution or *virtual radius* of measurement due to the electric field's finite size. The profile measurement at each point in the trace corresponds to a weighted spatial average of height near the sensor. This physical phenomenon acts to filter higher spatial frequencies from the surface profile in the same way that a stylus tip's dimensions prevent the tracking of ultrafine asperities. The spatial resolution of the FFC probe is not a fixed value, but rather a function of the average height of the surface measured. As the average height decreases, the FFC probe provides a finer spatial resolution.

Spatial resolution of the FFC probe along the profiling direction shall be equivalent to that of a 10 $\mu$m radius stylus or smaller. For FFC probes with the sensing element in the form of a disc as in Fig. 4-1(b), the lateral resolution perpendicular to the profiling direction should be a concern for the user when measuring surfaces that do not have a strong lay.

**4.4.6.2 FFC Probe Force.** The FFC probe contacts the surface via its nonconductive skid. The probing force must be sufficient for the skid to maintain contact with the surface during profiling.

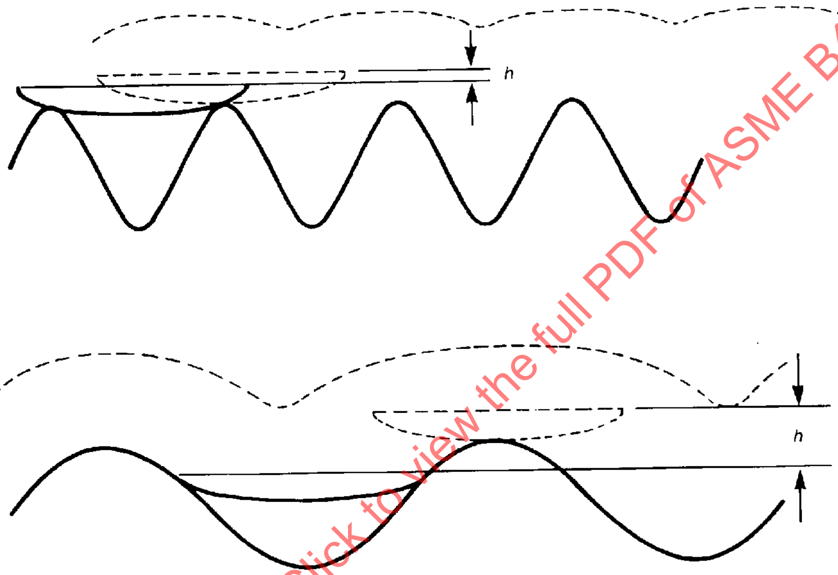
**4.4.6.3 FFC Probe Support (Skid).** The skid shall preferably have a radius in the direction of the trace of at least 50 times the cutoff.

**4.4.7 Possible Sources of Skid Errors.** If the skids undergo appreciable vertical displacement in moving over a surface, this displacement is subtracted from the probe motion (see Fig. 4-3). This displacement is dependent on the skid location and the wavelength of the surface waviness. In some cases smaller skids must be used because only a short length of surface can be measured. In such cases, the skid motion might cause significant errors on surfaces with large roughness values.

Single skid systems, where the skid leads or lags the probe, may produce another source of skid error as seen in Fig. 4-4. Here again, the skid vertical displacement is subtracted from the probe displacement. This may occur specifically for relatively fine finishes where an isolated peak in the surface occurs.

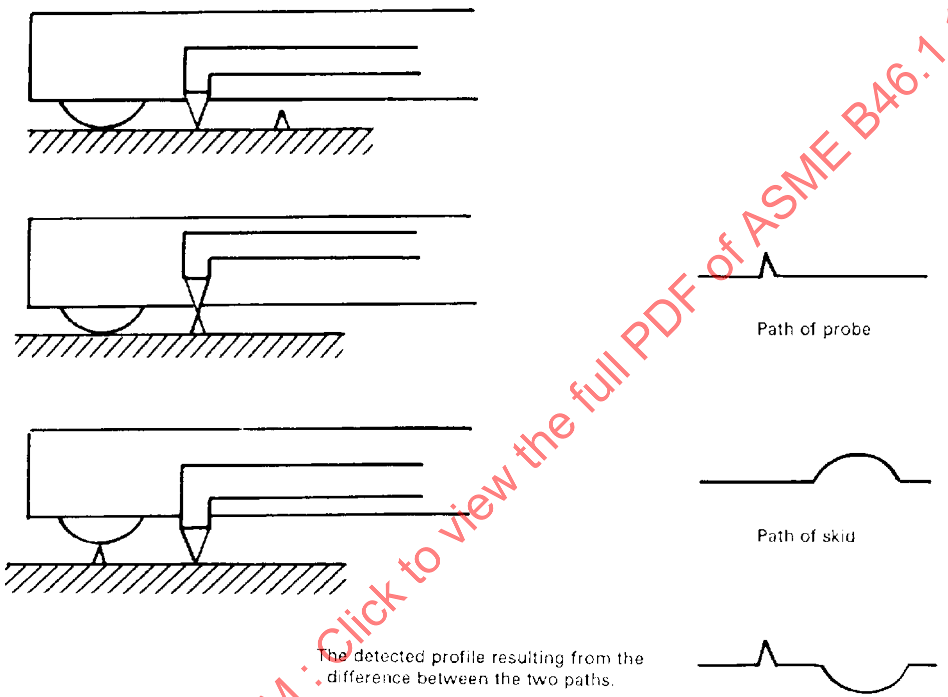
**4.4.8 Instrument Accuracy.** The $R_a$ indication of an instrument to a sinusoidal mechanical input of known amplitude and frequency within the amplitude and the cutoff range of the instrument shall not deviate by more than $\pm 7\%$ from the true $R_a$ value of the input.

**4.4.9 Operational Accuracy.** Instrument calibration for $R_a$ measurement should be checked using precision roughness specimens at one or two points in the measurement range depending on the manufacturer's instructions. If two precision reference specimens are used, one should be characterized by a large $R_a$ for checking calibration and the second by a small $R_a$ for checking linearity. *Stylus check* specimens should not be used for this purpose. If the $R_a$ measurement on either specimen differs by more than 10% of the calibrated value, instrument recalibration is required. For additional information on precision reference specimens, refer to Section 11.




GENERAL NOTES:
(a) This Fig. is not drawn to scale; the skid radius is shown smaller than it is in reality, and the roughness structure is shown larger in comparison with the probe assembly than it is in reality.
(b) Skid motion (dotted line) is subtracted from the probe motion (not shown).

**FIG. 4-3 EXAMPLES OF PROFILE DISTORTION DUE TO SKID MOTION**




GENERAL NOTE:
This Fig. is not drawn to scale; the skid radius is shown smaller than it is in reality.

**FIG. 4-4 EXAMPLE OF PROFILE DISTORTION**

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# SECTION 5 MEASUREMENT TECHNIQUES FOR AREA PROFILING

## 5.1 Scope of Section 5

Area profiling methods denote those techniques that produce a quantitative topographical map of a surface. Such a map often consists of a set of parallel profiles. This Section divides area profiling techniques into two classes, i.e., imaging and scanning methods. Instruments used to generate these topographic maps are generally Types II or III or modifications of Type I instruments. The instrument types are discussed in Section 2.

## 5.2 Recommendations

The topographic data can be used to calculate a variety of surface texture parameters. Section 1 contains terms and definitions of parameters relating to these area profiling techniques. The parameters defined there include $R_a$, $R_q$, $AR_a$, and $AR_q$. However, the measured values of these and other parameters depend on details of the technique used for the measurement. Area profiling instruments may be used to measure $AR_a$ and $AR_q$, provided the lateral resolution and the sampling length (or alternatively, the sampling area) are indicated for each measurement. Future revisions of this Standard may contain recommended procedures for filtering topographic maps and measuring surface parameters. In the meantime, it is important that the user understand thoroughly certain properties of the instrument, particularly system height resolution, height range, spatial resolution, sampling length, evaluation length, and evaluation area (discussed in Section 1) in order to appreciate the capabilities and limits of the instruments. In addition, it is important to determine whether the instrument detects height differences between raster profiles spaced along the $y$ direction and, if so, whether it routinely filters away those differences.

With a knowledge of the factors listed above, buyers and sellers can agree on meaningful specifications for surfaces as characterized by area profiling techniques. It is important to point out that the practices described in ASME Y14.36M do not apply entirely to this class of instruments.

## 5.3 Imaging Methods

In an imaging method, the radiation emitted or reflected from all points on the illuminated surface is simultaneously imaged on a video camera or an optical detector array. Therefore, the topographical data from all points on the surface are accumulated nearly simultaneously. Examples of imaging methods are phase measuring interferometric microscopy and vertical scanning interferometric microscopy.

## 5.4 Scanning Methods

These methods use a probe that senses the height variations of the surface. When the probe is raster scanned over the surface, a profile is generated through the collection of sequential measurements. The probing technique may be optical, electrical, or mechanical. Examples of scanning methods include optical focus-sensing systems, Nomarski differential profiling, stylus, scanning tunneling microscopy, atomic force microscopy, and scanning electron microscopy. Appendix E describes operating principles for several types of area profiling techniques.

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# SECTION 6 MEASUREMENT TECHNIQUES FOR AREA AVERAGING

## 6.1 Scope of Section 6

Area averaging methods denote those techniques that measure a representative area of a surface and produce quantitative results that depend on area averaged properties of the surface texture. They are to be distinguished from area profiling methods described in Section 5. Terms and definitions of parameters relating to area averaging techniques are contained in Section 1. When carefully used in conjunction with calibrated roughness comparison specimens or pilot specimens (described in Section 12), area averaging techniques may be used as comparators to distinguish the surface texture of parts manufactured by similar processes or to perform repetitive surface texture measurements.

## 6.2 Examples of Area Averaging Methods

There are a variety of area averaging techniques for estimating surface texture over an area. Commonly used quantitative methods include parallel plate capacitance, total integrated scatter, and angle resolved scatter. Appendix F describes operating principles for these area averaging methods.

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## SECTION 7

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## SECTION 8

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# SECTION 9 FILTERING OF SURFACE PROFILES

## 9.1 Scope of Section 9

This Section specifies the metrological characteristics of the 2RC filter and the phase correct Gaussian filter and their transmission bands as they are used in evaluating parameters for roughness and waviness. These filters and transmission bands are specified as they should be used in Type I profiling, contact, skidless instruments; Type IV contact, skidded, instruments; and Type V skidded instruments with parameters only. These filtering approaches may also be used in Type II, profiling noncontact instruments, and Type III, scanned probe microscopes. The instrument types are discussed in Section 2. Both types of filters are suitable for the evaluation of parameters of surface roughness defined in Section 1, except for $R_p$, $R_{pm}$, and $R_v$, where phase distortion from the 2RC filter causes errors for some types of surface undulations. Also, the 2RC filter does not separate roughness and waviness as efficiently as the Gaussian filter. Therefore, for evaluation of waviness parameters, only the Gaussian filter should be used. For more information on why filtering is required and on the difference between filter types, see Appendix G.

## 9.2 References

Section 1, Terms Related to Surface Texture

Section 2, Classification of Instruments for Surface Texture Measurement

Section 3, Terminology and Measurement Procedures for Profiling Contact, Skidless Instruments

Section 4, Measurement Procedures for Contact, Skidded Instruments

ISO 11562, Metrological Characterization of Phase Corrected Filters and Transmission Bands for Use in Contact Stylus Instruments

## 9.3 Definitions and General Specifications

### 9.3.1 General

*profile filter* — the mechanical, electrical (analog), or digital device or process which is used to separate the roughness profile from finer fluctuations and from the waviness profile or to separate the waviness profile from the roughness profile and, if necessary, the form error. Profile filters with long-wavelength cutoff provide a smooth mean line to a measured profile, thus providing a suitable, modified profile for the calculation of parameters of roughness or waviness with respect to that mean line.

*phase correct profile filters* — profile filters which do not cause phase shifts that lead to asymmetric profile distortions

### 9.3.2 Surface Lengths Associated With Filtering and Parameter Assessment

*roughness sampling length, $l$* — the nominal surface interval within which a surface roughness parameter is determined. It corresponds approximately to the longest spatial wavelength of profile fluctuations that may be measured. The roughness sampling length differs from the evaluation length and the traversing length. As defined in Section 1, the roughness sampling length is the sampling length specified to separate roughness profile irregularities from waviness profile irregularities.

*roughness long-wavelength cutoff, $\lambda_c$* — defined in Section 1. The cutoff of the filter is the nominal rating in millimeters (mm) of the long wavelength limit of the electrical (analog) or digital filter that attenuates the long wavelength waviness fluctuations of the surface profile to yield the roughness profile. When an electrical or digital filter is used, the roughness long-wavelength cutoff value determines and is equal to the roughness sampling length, i.e., $l = \lambda_c$.

Standard roughness long-wavelength cutoff values for all types of filters are 0.08 mm (0.003 in.), 0.25 mm (0.010 in.), 0.8 mm (0.03 in.), 2.5 mm (0.10 in.), or 8 mm (0.3 in.). If any other roughness sampling length value is used, it must be clearly specified.

*roughness short-wavelength cutoff, $\lambda_s$* — the spatial wavelength below which the fine asperities of the surface roughness profile are attenuated. The nominal values of this parameter are expressed in micrometers ($\mu$m). This attenuation may be realized in three ways: mechanically because of the finite tip radius, electrically by an antialiasing filter, or digitally by smoothing the data points. For digital instruments, the mechanical and electrical cutoff wavelengths should be smaller than the desired short-wavelength cutoff value which should be accomplished with a digital filter. The digital short-wavelength limit is stable whereas a mechanical or electrical short-wavelength limit may vary over time.

*waviness long-wavelength cutoff, $\lambda_{cw}$* — the spatial wavelength above which the widely spaced undulations of the waviness profile are attenuated. Form error can be separated from waviness on a surface by digital filtering with a Gaussian filter. When this is practiced, a waviness long-wavelength cutoff for the Gaussian filter must be specified.

*waviness short-wavelength cutoff, $\lambda_{sw}$* — the spatial wavelength, with nominal values typically in millimeters (mm), below which the roughness profile fluctuations of the surface profile are attenuated by electrical or digital filters. This rating is equivalent in value to the corresponding roughness long-wavelength cutoff ($\lambda_{sw} = \lambda_c$), but the filter transmission characteristic is the complement of the roughness long-wavelength cutoff filter transmission characteristic.

*evaluation length* — the length over which the values of surface parameters are determined

*roughness evaluation length, L* — the length over which roughness parameters are determined. The roughness evaluation length, wherever possible for statistical purposes, should consist of five roughness sampling lengths ($l$). The use of an evaluation length consisting of a number of sampling lengths different from five must be clearly indicated. The use of too few roughness sampling lengths in the roughness evaluation length could cause poor statistics of the resulting average parameter values.

*waviness evaluation length, $L_w$* — the evaluation length over which waviness parameters are determined. For waviness, the sampling length concept is no longer used. Only the waviness evaluation length $L_w$ and the waviness long-wavelength cutoff $\lambda_{cw}$ are defined. The waviness evaluation length can be several times the waviness long-wavelength cutoff for the purpose of achieving better statistics in the calculation of parameters.

*traversing length* — the length that the stylus traverses in order to obtain an evaluation length over which stable values of surface parameters can be calculated. It is usually longer than the evaluation length in order to keep the start and stop of the stylus scan from affecting the results. For digitally filtered roughness measurements, an adequate tracing length must be added before and after the evaluation length for the integration requirements of the digital filtering. For a roughness evaluation length of five sampling lengths, the traversing length is typically equal to at least six sampling lengths. For waviness, one half of a waviness long-wavelength cutoff is required at each end of the waviness evaluation length for filtering. As a result, the waviness traversing length is equal to the waviness evaluation length plus the length of one waviness long-wavelength cutoff $\lambda_{cw}$.

*transmission band* — for roughness or waviness, the range of wavelengths of sinusoidal components of the surface profile that are transmitted by the measuring instrument. This range is delineated by the values of the short-wavelength cutoff and the long-wavelength cutoff (see, for example, Figs. 9-1 and 9-2).

*weighting function (of a filter)* — the function for the mean line calculation that describes the smoothing process. This may be accomplished by applying either of the following expressions; the first is analytical, the second, digital:

$$z'(x_1) = \int_{-\infty}^{+\infty} S(x)\, z(x + x_1)dx$$

$$z'_i = \sum_{k=-n}^{n} a_k\, z_{i+k}$$

In the analytical expression above, $z(x + x_1)$ is the unfiltered profile as a function of position near a point $x_1$, $z'(x_1)$ is the filtered profile calculated for point $x_1$, and $S(x)$ is the weighting function. In the digital expression, $z'_i$ is the $i^{th}$ profile height in the filtered profile, $z_i$ is a profile height in the unfiltered profile, the $a_k$'s make up the weighting function, and the number of profile heights included in the weighting function is equal to $2n + 1$. Each type of cutoff (roughness short-wavelength cutoff $\lambda_s$, roughness long-wavelength cutoff $\lambda_c$, waviness short-wavelength cutoff $\lambda_{sw}$, and waviness long-wavelength cutoff $\lambda_{cw}$) has an associated weighting function (see, for example, Fig. 9-3).

*transmission characteristic (of a filter)* — the function that defines the magnitude to which the amplitude of a sinusoidal profile is attenuated as a function of its spatial frequency $f$ or spatial wavelength $\lambda$. The transmission characteristic of a filter is the Fourier transform of the weighting function of the filter.

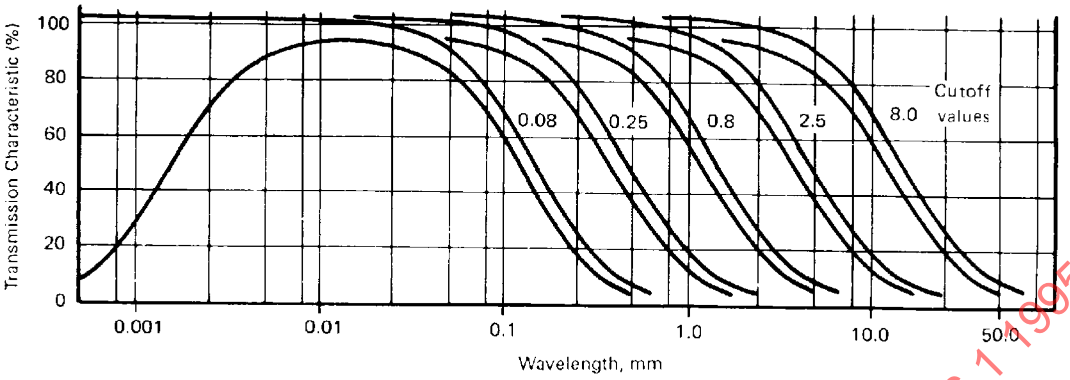


FIG. 9-1 WAVELENGTH TRANSMISSION CHARACTERISTICS FOR THE 2RC FILTER SYSTEM

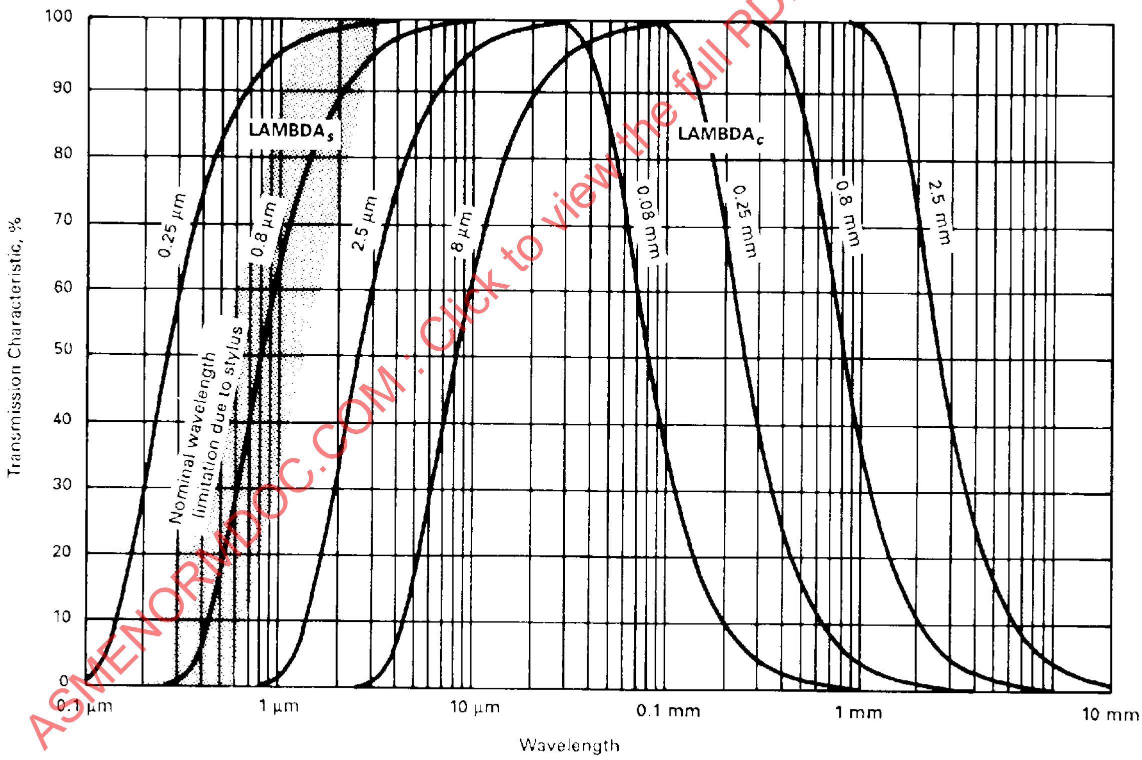


FIG. 9-2 GAUSSIAN TRANSMISSION CHARACTERISTICS TOGETHER WITH THE UNCERTAIN NOMINAL TRANSMISSION CHARACTERISTIC OF A 2 $\mu m$ STYLUS

Courtesy of Paul Scott

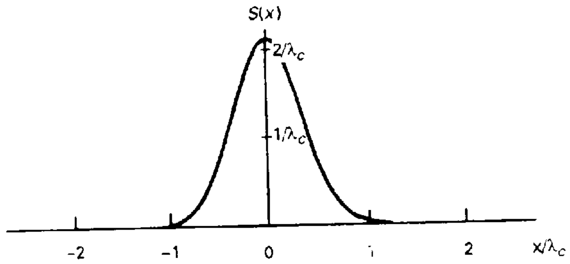


**FIG. 9-3 WEIGHTING FUNCTION OF THE GAUSSIAN PROFILE FILTER**



Each cutoff value (roughness short-wavelength cutoff $\lambda_s$, roughness long-wavelength cutoff $\lambda_c$, waviness short-wavelength cutoff $\lambda_{sw}$, and waviness long-wavelength cutoff $\lambda_{cw}$) has a distinct transmission characteristic (see, for example, Figs. 9-4 and 9-5).

*cutoff ratio* — for roughness or waviness, the ratio of the long-wavelength cutoff to the short-wavelength cutoff

### 9.4 2RC Filter Specification for Roughness

The 2RC filter consists of analog circuitry of two idealized RC filters in series. The capacitor and resistor values are selected to yield the desired transmission characteristic, consistent with the traverse speed of the instrument. This type of filtering can also be applied digitally by convolving an asymmetric, phase distorting weighting function, having the shape of the response of the 2RC electrical filter, with the unfiltered digital profile.

**9.4.1 The 2RC Transmission Band.** The electrical system for 2RC filtering must transmit surface wavelengths ranging from the designated long-wavelength cutoff point (cutoff $\lambda_c$) to 2.5 $\mu$m (0.0001 in.) (see Fig. 9-1). The transmission for a sinusoidal, mechanical input to the stylus shall be flat to within $\pm 7\%$ of unity over the spatial frequency passband region, except in the immediate vicinity of the cutoff wavelength.

**9.4.2 Long-Wavelength Cutoff.** The standard roughness long-wavelength cutoff values for the 2RC filter are listed in para. 9.3.2. The roughness long-wavelength cutoff $\lambda_c$ is the wavelength of the sinusoidal profile for which 75% of the amplitude is transmitted by the profile filter.

If no cutoff is specified for a measurement, then the appropriate cutoff value can be determined following the procedure detailed in Section 3. The long-wavelength cutoff must be specified in all cases on drawings created or revised after this Standard is published. For drawings created or revised earlier, the 0.8 mm value was assumed if no value was specified.

#### 9.4.3 Transmission Characteristics

**9.4.3.1 Short-Wavelength Transmission Characteristic.** The transmission characteristic near the short-wavelength cutoff of the roughness transmission band shall be equivalent to that produced by two idealized low-pass RC networks, with equal time constants, in series. The transfer function is:

$$\frac{\text{Filter Output}}{\text{Filter Input}} = (1 - ik\lambda_s/\lambda)^{-2}$$

where the short wavelength roughness cutoff $\lambda_s$ is less than or equal to 2.5 $\mu$m (0.0001 in.), $i = \sqrt{-1}$, and $k = 1/\sqrt{3} = 0.577$.

The percent limits of the transmission characteristic near the short-wavelength cutoff are calculated from the following equations:

$$\text{Upper Limit} = 103$$

$$\text{Lower Limit} = \frac{97}{1 + 0.39\,(2.5\ \mu\text{m}/\lambda)^2}$$

These two limiting functions are shown on the left hand side of Fig. 9-1. These limits are in addition to the allowable error of the amplitude transmission of the roughness transmission band stated in para. 9.4.1.

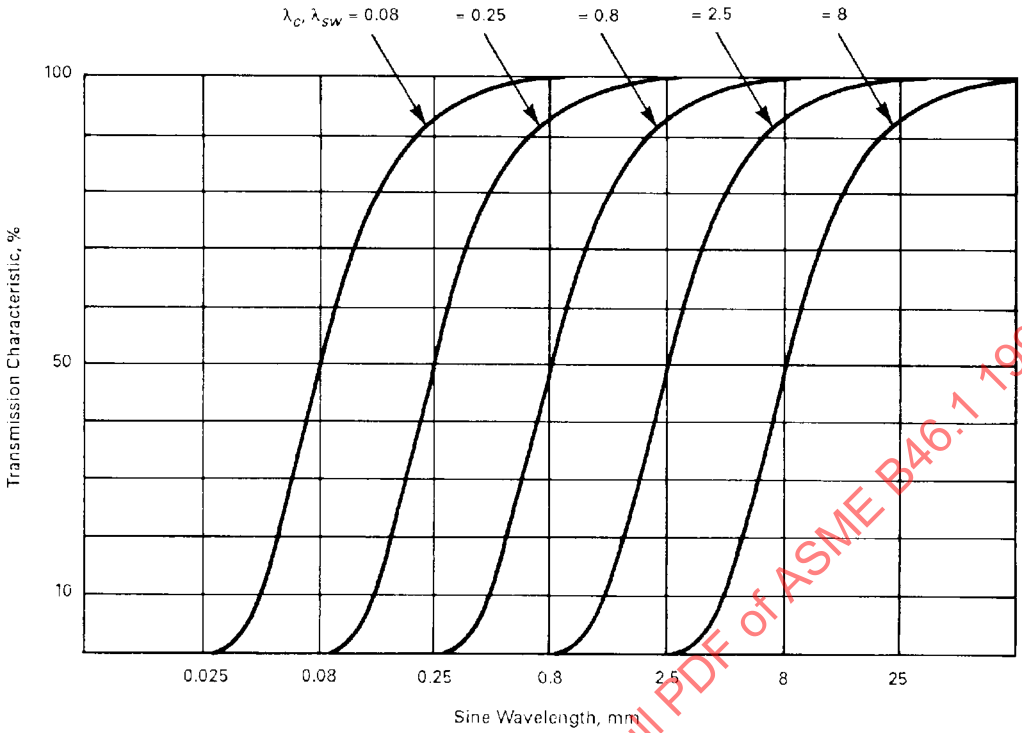


**FIG. 9-4 GAUSSIAN TRANSMISSION CHARACTERISTIC FOR THE WAVINESS SHORT-WAVELENGTH CUTOFF AND THE ROUGHNESS MEAN LINE HAVING CUTOFF WAVELENGTHS $\lambda_c$ = 0.08, 0.25, 0.8, 2.5, AND 8.0 mm**

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**9.4.3.2 Long-Wavelength Transmission Characteristic.** The transmission characteristic on the long-wavelength end of the roughness transmission band shall be that produced by the equivalent of two idealized, high-pass RC networks, with equal time constants, in series. The transfer function of this system is:

$$\frac{\text{Filter Output}}{\text{Filter Input}} = (1 - ik\,\lambda/\lambda_c)^{-2}$$

where $i$ and $k$ are defined above.

The percent transmission limits of this transfer function are calculated from the following equations:

$$\text{Upper Limit} = \frac{103}{1 + 0.29\,(\lambda/\lambda_c)^2}$$

$$\text{Lower Limit} = \frac{97}{1 + 0.39\,(\lambda/\lambda_c)^2}$$

These limits are given in Table 9-1 and are graphed in Fig. 9-1. These limits are in addition to the allowable error of the amplitude transmission of the roughness transmission band stated in para. 9.4.1.

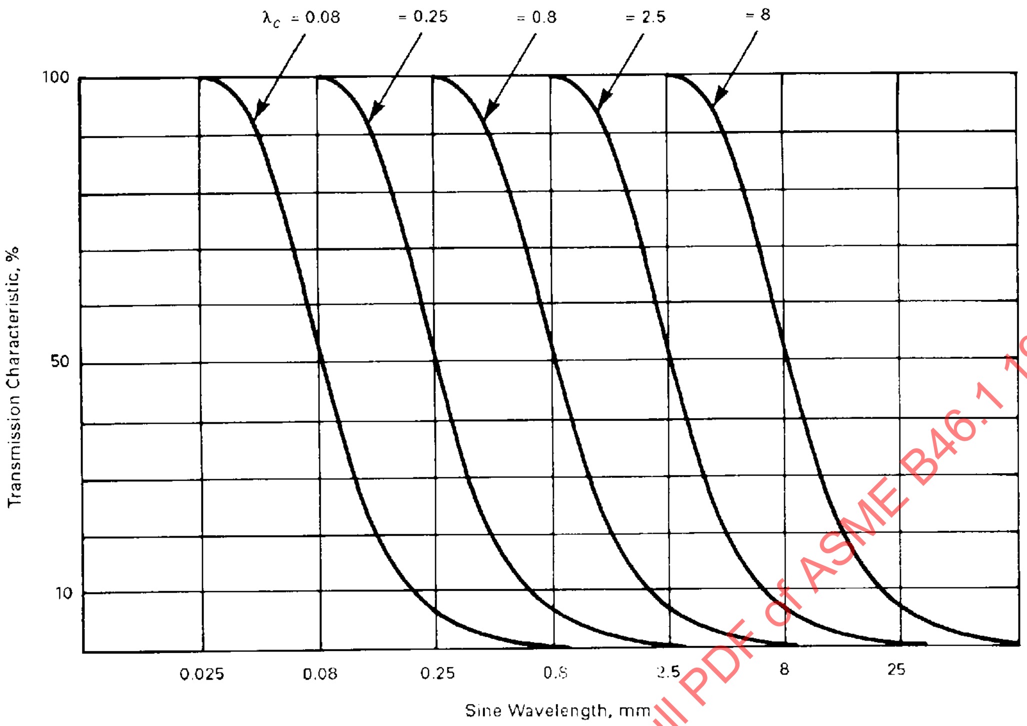


**FIG. 9-5 GAUSSIAN TRANSMISSION CHARACTERISTIC FOR THE ROUGHNESS LONG-WAVELENGTH CUTOFF HAVING CUTOFF WAVELENGTHS $\lambda_c$ = 0.08, 0.25, 0.8, 2.5, AND 8.0 mm**





**9.4.4 2RC Filter Long-Wavelength Roughness Weighting Function.** 2RC filters can be realized either in electronic analog form or digitally. In the digital form, the long-wavelength roughness filter weighting function that is convolved through the digital profile has the form:

$$S(x) = (A/\lambda_c)[2 - (A|x|/\lambda_c)]e^{-(A|x|/\lambda_c)}$$

where $A = 3.64$ for 75% transmission at $\lambda_c$, $x$ is the position in millimeters from the origin of the weighting function ($-\infty < x < 0$), and $\lambda_c$ is the long wavelength roughness cutoff.

## 9.5 Phase Correct Gaussian Filter for Roughness

**9.5.1 Phase Correct Gaussian Filter Mean Line (The Mean Line).** This mean line is comprised of the waviness and any other long spatial wavelength components in the profile which are not associated with the surface roughness. The mean line is determined for any point of the measured profile by taking a Gaussian weighting function average of the adjacent points as described below.

**9.5.2 Gaussian Filter Roughness Profile.** The roughness profile is composed of the deviations of the measured profile from the Gaussian mean line.

**TABLE 9-1 LIMITS FOR THE TRANSMISSION CHARACTERISTICS FOR 2RC LONG-WAVELENGTH CUTOFF FILTERS**

| Spatial Wavelength | | Long-Wavelength Cutoffs | | | | |
|---|---|---|---|---|---|---|
| mm | (in.) | 0.08 mm (0.003 in.) | 0.25 mm (0.010 in.) | 0.8 mm (0.030 in.) | 2.5 mm (0.100 in.) | 8.0 mm (0.300 in.) |
| 0.008 | 0.0003 | 97–103 | ... | ... | ... | ... |
| 0.010 | 0.0004 | 96–102 | ... | ... | ... | ... |
| 0.025 | 0.001 | 93–100 | 97–103 | ... | ... | ... |
| 0.05 | 0.002 | 84–93 | 95–102 | ... | ... | ... |
| 0.08 | 0.003 | 70–80 | 93–100 | 97–103 | ... | ... |
| 0.1 | 0.004 | 60–71 | 91–98 | 96–102 | ... | ... |
| 0.25 | 0.01 | 20–27 | 70–80 | 93–100 | 97–103 | ... |
| 0.5 | 0.02 | 6–8 | 38–48 | 84–93 | 95–102 | ... |
| 0.8 | 0.03 | 2–3 | 19–26 | 70–80 | 93–100 | 97–103 |
| 1.0 | 0.04 | ... | 13–18 | 60–71 | 91–98 | 96–102 |
| 2.5 | 0.1 | ... | 2–3 | 20–27 | 70–80 | 93–100 |
| 5.0 | 0.2 | ... | ... | 6–8 | 38–48 | 84–93 |
| 8.0 | 0.3 | ... | ... | 2–3 | 19–26 | 70–80 |
| 10.0 | 0.4 | ... | ... | ... | 13–18 | 60–71 |
| 25.0 | 1.0 | ... | ... | ... | 2–3 | 20–27 |
| 50.0 | 2.0 | ... | ... | ... | ... | 6–8 |
| 80.0 | 3.0 | ... | | ... | ... | 2–3 |

It is determined by subtracting the mean line from the measured profile.

**9.5.3 Long-Wavelength Cutoff of the Gaussian Phase Correct Filter.** For the phase correct Gaussian filter, the long-wavelength cutoff $\lambda_c$ is the spatial wavelength of a sinusoidal profile for which 50% of the amplitude is transmitted by the profile filter. Standard long-wavelength roughness cutoff values are the same for both the Gaussian filter and the 2RC filter and are given in para. 9.3.2. If no cutoff is specified for a measurement, then an appropriate cutoff can be determined by following the procedure detailed in Section 3. The long-wavelength cutoff must be specified in all cases on drawings created or revised after this Standard is published. For drawings created or revised earlier, the 0.8 mm value was assumed, if not specified.

**9.5.4 Short-Wavelength Cutoff of the Gaussian Roughness Profile.** The cutoff wavelength $\lambda_s$ is the spatial wavelength of a sinusoidal profile for which 50% of the amplitude is transmitted by the short-wavelength cutoff filter.

**9.5.5 Short-Wavelength Transmission Characteristic.** The transmission characteristic in the region of the short-wavelength cutoff is expressed as the fraction to which the amplitude of a sinusoidal profile is attenuated as a function of its spatial wavelength. This transmission characteristic is produced by a Gaussian profile weighting function as defined in this Section. The equation is:

$$\frac{\text{Filter Output}}{\text{Filter Input}} = e^{-\pi(\alpha\lambda_s/\lambda)^2}$$

where $\alpha = \sqrt{[ln(2)]/\pi} = 0.4697$ and $\lambda_s$ is the roughness short-wavelength cutoff. Examples of the transmission characteristic for several values of $\lambda_s$ (and also $\lambda_c$) are given in Fig. 9-2.

**9.5.6 Weighting Function for the Roughness Short-Wavelength Cutoff.** The weighting function of the Gaussian phase correct filter for the roughness short-wavelength cutoff has a Gaussian form, similar to that to be discussed in para. 9.5.7 and shown in Fig. 9-3. The equation for the weighting function $S(x)$ is as follows:

$$S(x) = (\alpha\lambda_s)^{-1}\, e^{-\pi[x/(\alpha\lambda_s)]^2}$$

where $x$ is the lateral position from the mean of the weighting function. The direct result of this filtering process is a smoothed profile, that is, one whose short wavelengths are attenuated.

**9.5.7 Weighting Function for the Roughness Long-Wavelength Cutoff.** The weighting function of the Gaussian phase correct filter for the roughness long-wavelength cutoff (Fig. 9-3) has a Gaussian form. With the long-wavelength cutoff $\lambda_c$, the equation is:

$$S(x) = (\alpha\lambda_c)^{-1}\, e^{-\pi[x/(\alpha\lambda_c)]^2}$$

In this case, the smoothed profile that results from applying the filter is the roughness mean line, and the roughness profile is found by subtracting this mean line from the original measured profile.

**9.5.8 Transmission Characteristic of the Gaussian-Filtered Waviness Profile (Roughness Mean Line).** The transmission characteristic of the roughness mean line is determined from the weighting function $S(x)$ by means of the Fourier transform (see Section 1) and is given in Fig. 9-4. The transmission characteristic for the mean line has the following equation:

$$\frac{\text{Filter Output}}{\text{Filter Input}} = e^{-\pi(\alpha\lambda_c/\lambda)^2}$$

**9.5.9 Transmission Characteristic of the Gaussian-Filtered Roughness Profile.** The transmission characteristic of the Gaussian filtered roughness profile (see Figs. 9-2 and 9-5) is the complement to the transmission characteristic of the roughness mean line, as defined in para. 9.5.8, because the roughness profile is the difference between the measured profile and the roughness mean line. The equation is therefore given by:

$$\frac{\text{Filter Output}}{\text{Filter Input}} = 1 - e^{-\pi(\alpha\lambda_c/\lambda)^2}$$

**9.5.10 Errors of Approximations to the Gaussian Filter.** No tolerance values are given for Gaussian filters as they were for 2RC filters in para. 9.4.3. Instead, a graphical representation of the deviations in transmission of the realized filter from the Gaussian filter shall be given as a percentage of unity transmission over the wavelength range from 0.01 $\lambda_c$ to 100 $\lambda_c$. An example of the deviation curve for a phase correct filter with triangular weighting function with respect to the transmission characteristic of an ideal Gaussian filter is given in Fig. 9-6.

**9.5.11 Transmission Band.** The transmission band for roughness for the Gaussian filter is the range of wavelengths of the surface profile that are transmitted by the short- and long-wavelength cutoff roughness filters. The limits are defined by the values of the roughness long-wavelength cutoff and short-wavelength cutoff listed in Table 9-2. The transmission band over the spatial wavelength domain (see Fig. 9-2), including the attenuation at the band limits, comprises the instrument transmission characteristic, and therefore should be taken into account in any surface roughness measurement. If the short wavelength limit is set at too high a value, then peak structures of interest may be attenuated and peak related parameters may be correspondingly erroneous. If the short wavelength limit is set at too low a value, then undesirable fine structure will be included in the filtered profile and contribute to parameter results.

**9.5.12 Cutoff Ratio.** The ratio of the long-wavelength cutoff $\lambda_c$ to the short-wavelength cutoff $\lambda_s$ of a given transmission band is expressed as $\lambda_c/\lambda_s$. If not otherwise specified, the values of $\lambda_s$ and the cutoff ratio may be obtained from Table 9-2 provided that the long-wavelength cutoff $\lambda_c$ is known. The sampling interval (point spacing) should be less than one fifth of the short-wavelength cutoff in order to accurately include all spatial wavelengths that contribute to the filtered profile.

The values of stylus radius shown in Table 9-2 provide the transmission band limits as listed without the filtering effects of the stylus intruding into the transmission band. If another cutoff ratio is deemed necessary to satisfy an application, this ratio must be specified. The recommended alternative cutoff ratios are 100, 300, or 1,000.

## 9.6 Filtering for Waviness

The waviness profile is only determined by the use of phase correct Gaussian filters to separate roughness profiles from the total profile, as this filtering separates the two components of the total profile in a clear manner. As stated in para. 9.5.8, the transmission characteristic for the roughness mean line has the following equation:

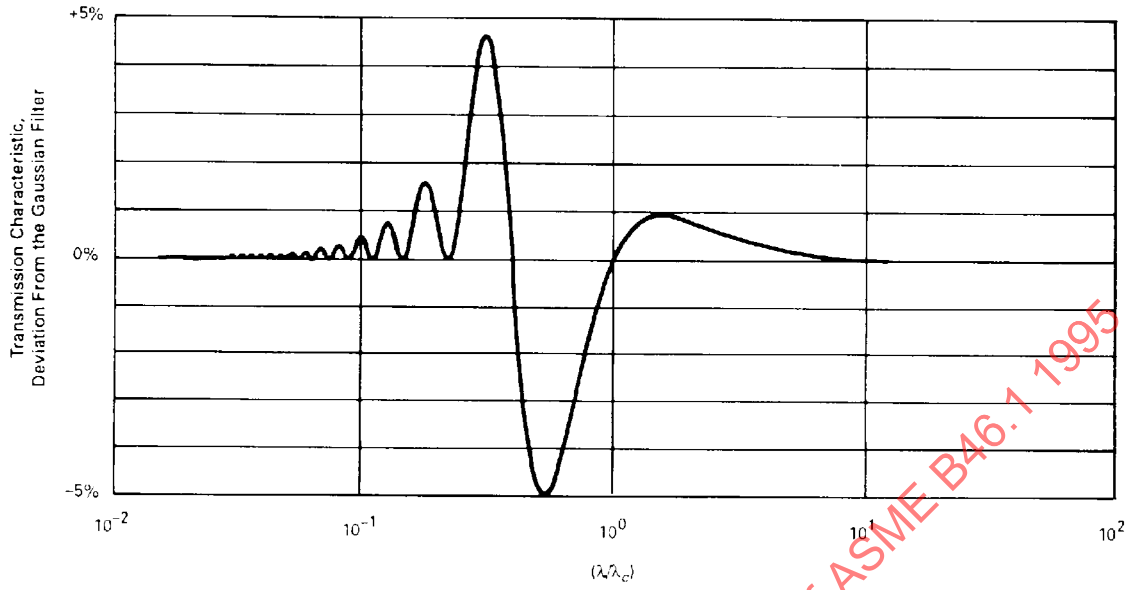


**FIG. 9-6 EXAMPLE OF A DEVIATION CURVE OF A REALIZED PHASE CORRECTED FILTER FROM THE IDEAL GAUSSIAN FILTER AS A FUNCTION OF SPATIAL WAVELENGTH**



$$\frac{\text{Filter Output}}{\text{Filter Input}} = e^{-\pi(\alpha\lambda_c/\lambda)^2}$$

The profile representing waviness and form error is then identical to the roughness mean line and is equal to the subtraction of the roughness profile from the total profile.

**9.6.1 Gaussian Filter Waviness Profile.** The waviness profile is the roughness mean line as described in para. 9.6 after further separation from the form error (or straightness) profile.

**9.6.2 Waviness Long-Wavelength Cutoff and Evaluation Length.** The waviness evaluation length can consist of one or more waviness cutoff lengths $\lambda_{cw}$ to separate form error at the long-wavelength waviness limit. The cutoff value $\lambda_{cw}$ may be realized by using a Gaussian filter as described below or by least squares methods over profile lengths equal to the waviness cutoff $\lambda_{cw}$. The ratio of $\lambda_{cw}/\lambda_c$ shall be 10/1 unless otherwise specified. Standard values for $\lambda_c$ and $\lambda_{cw}$ are given in Table 9-3.

**9.6.3 Waviness Traversing Length.** The traversing lengths for waviness when using a Gaussian filter to separate waviness and form error are listed in Table 9-3.

**9.6.4 Methods for Determining the Waviness Mean Line.** If the total unfiltered profile contains intentional contour or form deviation, then this should first be removed by least squares fitting. The remaining profile may still contain form errors in addition to waviness and roughness. The further separation of form error from waviness may be accomplished by least squares methods as mentioned in para. 9.6.2 or by phase correct filtering. This is ac-

**TABLE 9-2 STANDARD CUTOFFS FOR GAUSSIAN FILTERS AND ASSOCIATED CUTOFF RATIOS**

| $\lambda_c$, mm (in.) | $\lambda_s$, $\mu$m (in.) | $\lambda_c / \lambda_s$, (Approx.) | $r_{tip}$, $\mu$m (in.) | Max Sampling Interval, $\mu$m (in.) |
|---|---|---|---|---|
| 0.08 (0.003) | 2.5 (0.0001) | 30 | 2 (0.00008) or less [Note (1)] | 0.5 (0.00002) |
| 0.25 (0.01) | 2.5 (0.0001) | 100 | 2 (0.00008) or less [Note (2)] | 0.5 (0.00002) |
| 0.8 (0.03) | 2.5 (0.0001) | 300 | 2 (0.00008) or less | 0.5 (0.00002) |
| 2.5 (0.10) | 8 (0.0003) | 300 | 5 (0.0002) or less | 1.5 (0.00006) |
| 8 (0.3) | 25 (0.001) | 300 | 10 (0.0004) or less | 5 (0.0002) |

NOTES:
(1) With a nonstandard stylus tip radius of 0.5 $\mu$m, the cutoff ratio for $\lambda_c$ = 0.08 mm may be set equal to 100, provided $\lambda_s$ = 0.8 $\mu$m and the maximum point spacing = 0.16 $\mu$m.
(2) With a nonstandard stylus tip radius of 0.5 $\mu$m, the cutoff ratio for $\lambda_c$ = 0.25 mm may be set equal to 300, provided $\lambda_s$ = 0.8 $\mu$m and the maximum point spacing = 0.16 $\mu$m.

**TABLE 9-3 STANDARD VALUES FOR THE WAVINESS LONG-WAVELENGTH CUTOFF ($\lambda_{cw}$) AND RECOMMENDED MINIMUM VALUES FOR THE WAVINESS TRAVERSING LENGTH**

| $\lambda_c$ | | $\lambda_{cw}$ | | Minimum Traversing Length When Using Gaussian Filter | |
|---|---|---|---|---|---|
| mm | (in.) | mm | (in.) | mm | (in.) |
| 0.08 | (0.003) | 0.8 | (0.03) | 1.6 | (0.06) |
| 0.25 | (0.01) | 2.5 | (0.1) | 5 | (0.2) |
| 0.8 | (0.03) | 8 | (0.3) | 16 | (0.6) |
| 2.5 | (0.1) | 25 | (1) | 50 | (2) |
| 8 | (0.3) | 80 | (3) | 160 | (6) |

complished in a manner similar to that discussed in para. 9.5.7, by applying the Gaussian filter to the roughness mean line, with a cutoff value equal to the waviness long-wavelength cutoff length $\lambda_{cw}$. The weighting function $S(x)$ for this filter is given by the equation:

$$S(x) = (\alpha\lambda_{cw})^{-1}\, e^{-\pi[x/(\alpha\lambda_{cw})]^2}$$

In order to minimize end effects when using a Gaussian filter, the traversing length should include half a waviness cutoff on each end of the evaluation length, so that the traverse should be equal to at least twice the waviness long-wavelength cutoff (see Table 9-3).

**9.6.5 Waviness Transmission Band.** The limits of the waviness transmission band are formed by a Gaussian filter at the short-wavelength boundary at $\lambda_c$ and by the cutoff $\lambda_{cw}$ on the long-wavelength boundary.

**9.6.5.1 Short-Wavelength Waviness Transmission Characteristic.** The waviness transmission characteristic in the region of the short-wavelength cutoff ($\lambda_{sw} = \lambda_c$), is expressed as the fraction to which the amplitude of a sinusoidal profile is attenuated as a function of its spatial wavelength. This transmission characteristic is produced by a Gaussian profile weighting function as defined in para. 9.5.6.

**9.6.5.2 Long-Wavelength Waviness Transmission Characteristic.** The form error may be removed by truncation or by phase correct Gaussian filtering. If the latter, then the long-wavelength waviness transmission characteristic is that produced by a Gaussian profile weighting function as defined in para. 9.5.7. In this case, the transmission characteristic for waviness at the $\lambda_{cw}$ limit is given by the expression:

$$\frac{\text{Filter Output}}{\text{Filter Input}} = 1 - e^{-\pi(\alpha\lambda_{cw}/\lambda)^2}$$

The form error line then is the mean line for the waviness profile.

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## SECTION 10

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# SECTION 11 SPECIFICATIONS AND PROCEDURES FOR PRECISION REFERENCE SPECIMENS

## 11.1 Scope of Section 11

This Section specifies the characteristics of specimens for the calibration of instruments to measure surface roughness. Precision reference specimens are intended for use in the field calibration of instruments for measuring roughness average or surface profile. They are not intended to have the appearance or characteristics of commonly produced surfaces, nor are they intended for use in visual or tactile comparisons. The calibration of the existing wide range of instruments, in all modes of operation, calls for more than one type of calibration specimen. Each calibrated specimen may have a limited range of application according to its own characteristics and those of the instrument to be calibrated. The validity of the calibration of an instrument will be dependent on the correct association of the characteristics of the calibration specimen with the machine features to be calibrated. In this Section, specifications are given for surface contour, material, accuracy, uniformity, flatness, and a method for determining assigned values for different types of specimens.

## 11.2 References

Section 1, Terms Related to Surface Texture

Section 2, Classification of Instruments for Surface Texture Measurement

Section 3, Terminology and Measurement Procedures for Profiling, Contact, Skidless Instruments

Section 4, Measurement Procedures for Contact, Skidded Instruments

Much of the technical information, including tables, has been adapted from ISO 5436:1985, Calibration Specimens — Stylus Instruments — Types, Calibration and Use of Specimens.

## 11.3 Definitions

*precision reference specimen* — a specimen having accurately determined standardized characteristics for testing or establishing one or more features of the performance of an instrument

Other definitions of terms are given in Section 1.

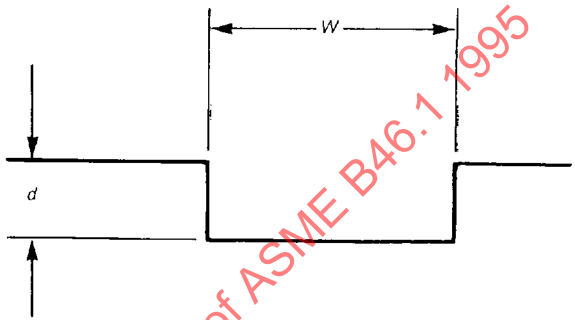



FIG. 11-1 TYPE A1 GROOVE

## 11.4 Reference Specimens: Profile Shape and Application

The profile of the specimen depends upon the intended use of the specimen, i.e., for testing amplification, stylus condition, parameter measurements, or overall instrument performance. To cover the range of requirements, four types of specimens are described below, each of which may have a number of variants.

**11.4.1 Amplification (Step Height) — Type A.** The specimens intended for checking the vertical magnification of profile recording instruments have grooves or plateaus surrounded by flat surface areas. The grooves or plateaus themselves are generally flat with sharp edges (as in Fig. 11-1), but these features may also be rounded, as in Fig. 11-2.

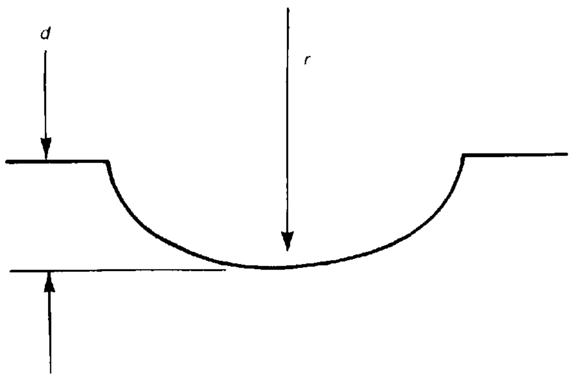



**FIG. 11-2 TYPE A2 GROOVE**

**11.4.2 Stylus Condition — Type B.** The specimens intended primarily for checking the condition of the stylus tip consist of grooves or edges of different types to be discussed in para. 11.7.2.

**11.4.3 Parameter Measurements — Type C.** The specimens intended for verifying the accuracy of parameter readout have a grid of repetitive grooves of simple shape (e.g., sinusoidal, triangular, or arcuate). Specimens for parameter calibration are classified as Type C.

**11.4.4 Overall Instrument Performance — Type D.** The specimens intended for overall checks of instrument performance simulate workpieces containing a wide range of crest spacings. This type of specimen has an irregular profile.

## 11.5 Physical Requirements

The material characteristics for the reference specimen, the size of the specimen, and the waviness height limit are defined in this Section.

**11.5.1 Materials.** The material used shall be hard enough to ensure adequate life in relation to cost. Its surface shall be smooth and flat enough not to affect the evaluation of the grooves. Glass, fused silica, or other material harder than 500 Vickers (HV) or 49 Rockwell C are favored.

**11.5.2 Size of the Specimen.** For specimens with roughness profiles, the operative area shall be large enough to provide for the traversing length required by other sections of this Standard for all intended determinations. A single specimen or several kinds of specimens may be provided on a single block.

**11.5.3 Waviness Limit.** For specimens with waviness profiles, the waviness, measured with respect to a flat datum, shall have waviness height, $W_t$, no greater than the values shown in Fig. 11-3. Step height specimens shall have an overall peak-to-valley flatness that is less than 60 nm or 1% of the step height being examined, whichever is greater.

## 11.6 Assigned Value Calculation

At the time of manufacture or before distribution, each precision reference specimen shall have an assigned value clearly marked near the designated measuring area of the specimen.

**11.6.1 Assigned Value of Shop Grade Specimens.** For shop grade specimens, the assigned value shall be the mean of five uniformly distributed readings taken on the designated measuring area:

$$\text{Assigned Value} = (R_1 + R_2 + R_3 + R_4 + R_5)/5$$

**11.6.2 Assigned Value of Reference Grade Specimens.** For reference grade specimens, the assigned value shall be the mean of composite values from at least eight uniformly distributed locations on the designated measuring area:

$$\text{Assigned Value} = (V_1 + V_2 + V_3 + V_4 + V_5 + V_6 + V_7 + V_8)/8$$

The composite value $V_i$ of each location shall consist of the mean of two individual readings:

$$V_i = (R_{i1} + R_{i2})/2$$

where $i = 1, 2, \ldots, 8$.

**11.6.3 Assigned Value of Stylus Check Specimens.** For the determination of the assigned $R_a$ values of stylus check specimens for use with averaging instruments, the tip radius must be held to 10 $\mu$m ± 2 $\mu$m as measured in the plane perpendicular to the

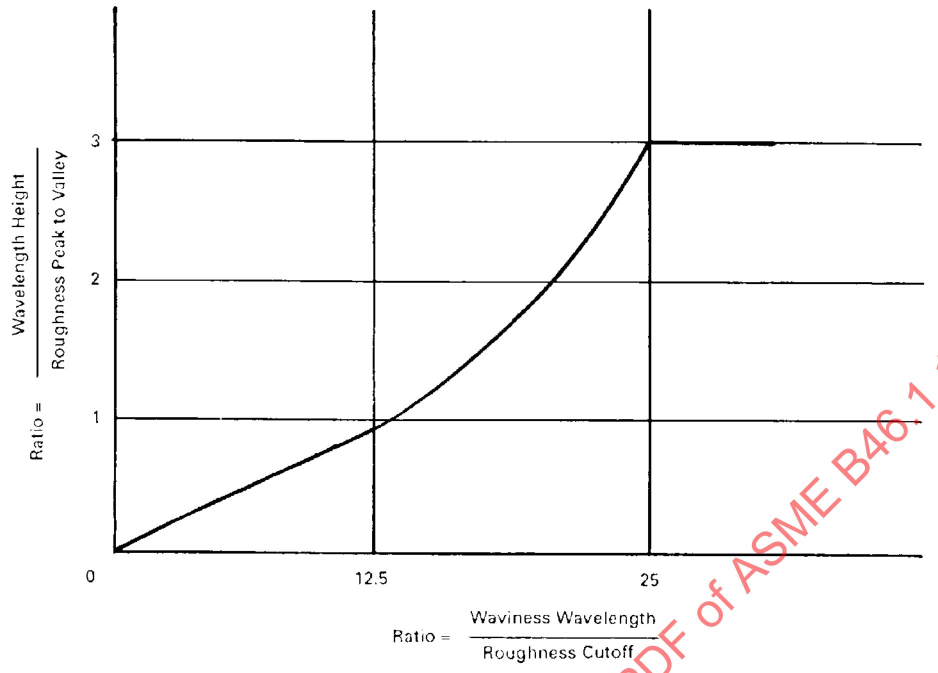



**FIG. 11-3 ALLOWABLE WAVINESS**



measured surface and in the direction of stylus motion. See also Sections 3 and 4.

### 11.7 Mechanical Requirements

**11.7.1 Types A1 and A2.** Type A1 specimens have calibrated plateau heights or groove depths (see Fig. 11-1) with nominal values shown in Table 11-1. The calibrated step height is shown as the distance *d* in Fig. 11-4. A pair of continuous straight mean lines (*A* and *B*) are drawn to represent the level of the outer surface. Another line represents the level of the groove or plateau. Both types of lines extend symmetrically about the center. The outer surface on each side of the groove is to be ignored for a sufficient length $w_1$ to avoid the influence of any rounding of the corners. The surface at the bottom of the groove is assessed only over the central third of its width. The portions to be used in the assessment are also shown. As long as the curvature of the step edges does not extend out to the offset distance $w_1$, the offset should be as small as possible to improve precision of the height measurement. The specimen should be aligned with the plane of the trace path.

For Type A2, shown in Fig. 11-2, a mean line representing the upper level is drawn over the groove. The depth shall be assessed from the upper mean line to the lowest point of the groove. Nominal values of groove depth and radius are shown in Table 11-2.

If a skid is used with an instrument for assessing these types of specimens, it shall not cross a groove at the same time that the probe crosses the groove being measured. Tolerances on the specimens are shown in Table 11-3.

**11.7.2 Types B1, B2, and B3.** The stylus condition is evaluated by measurement of Type B specimens.

The Type B1 specimen has a set of four grooves. The widths of the individual grooves are nominally 20 $\mu$m, 10 $\mu$m, 5 $\mu$m, and 2.5 $\mu$m (see Fig. 11-5). The size and condition of the stylus is estimated from the profile graphs (see Table 11-4).

**TABLE 11-1 NOMINAL VALUES OF DEPTH OR HEIGHT AND EXAMPLES OF WIDTH FOR TYPE A1**

| Depth, *d* | Width, *w* |
|---|---|
| 0.3 | 100 |
| 1.0 | 100 |
| 3.0 | 200 |
| 10 | 200 |
| 30 | 500 |
| 100 | 500 |

GENERAL NOTE: Values are in μm.

**TABLE 11-2 NOMINAL VALUES OF DEPTH AND RADIUS FOR TYPE A2**

| Depth, *d* (μm) | Radius, *r* (mm) |
|---|---|
| 1.0 | 1.5 |
| 3.0 | 1.5 |
| 10 | 1.5 |
| 30 | 0.75 |
| 100 | 0.75 |

**TABLE 11-3 TOLERANCES FOR TYPES A1 AND A2**

| Nominal Value, μm | Tolerance on Nominal Value, % | Uncertainty of Measurement in Calibrated Mean Depth [Note(1)], % | Uniformity — One Standard Deviation from the Calibrated Mean, % |
|---|---|---|---|
| 0.3 | ±20 | ±3 | 3 |
| 1 | ±15 | ±2 | 2 |
| 3 | ±10 | ±2 | 2 |
| 10 | ±10 | ±2 | 2 |
| 30 | ±10 | ±2 | 2 |
| 100 | ±10 | ±2 | 2 |

NOTE:
(1) Assumed in this document to be at the two standard deviation or approximately 95% confidence level.

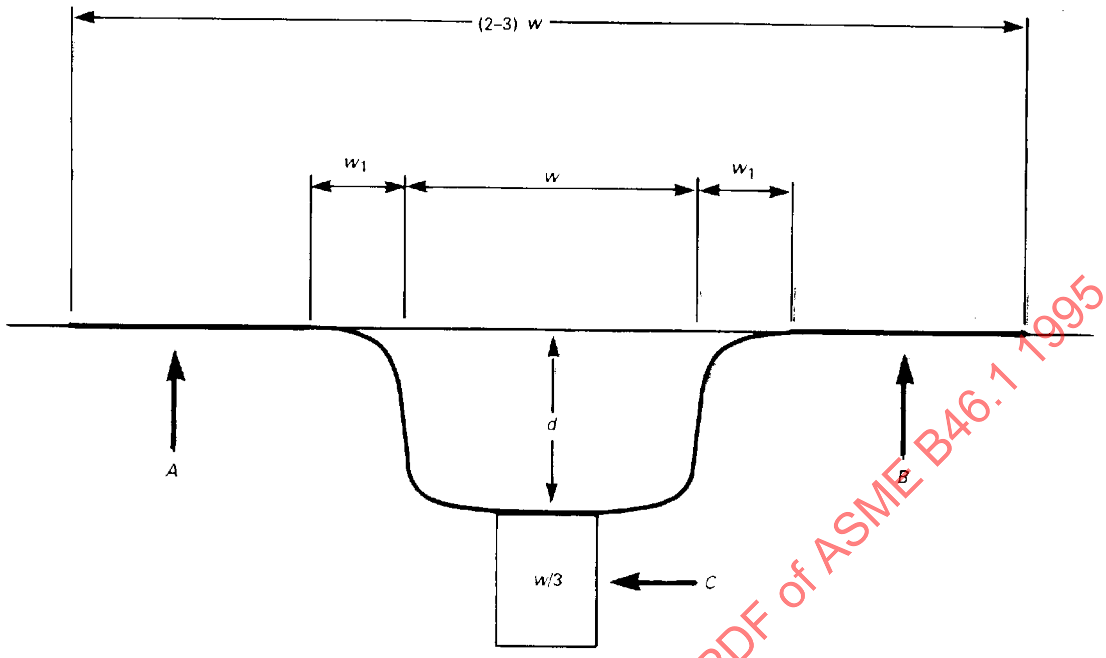



FIG. 11-4 ASSESSMENT OF CALIBRATED VALUES FOR TYPE A1

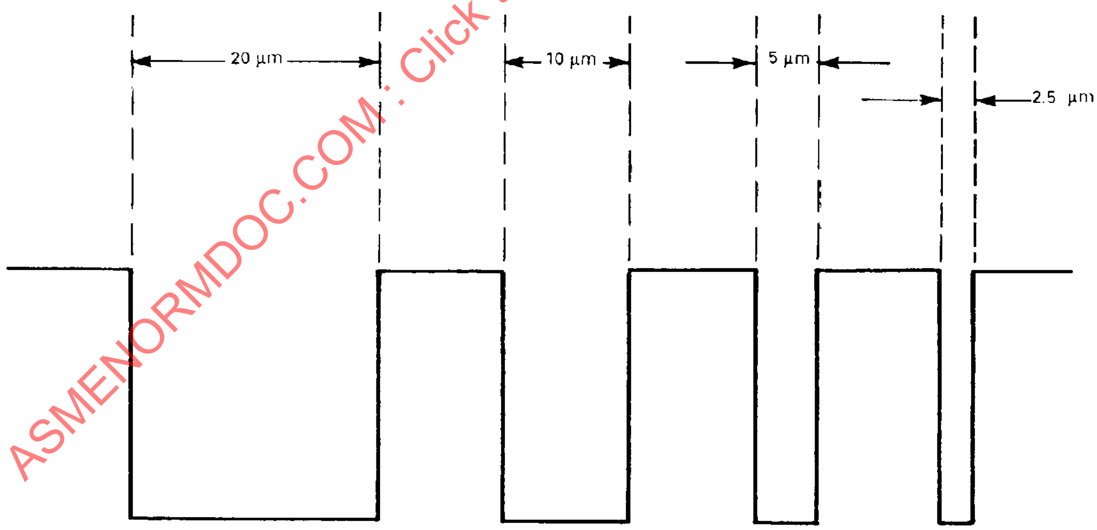



FIG. 11-5 TYPE B1 GROOVES — SET OF 4 SLITS

**TABLE 11-4 TIP SIZE ESTIMATION FROM THE PROFILE GRAPH FOR TYPE B1 [NOTE (1)]**

| Stylus Penetration of Grooves | Approximate Tip Size |
|---|---|
| First groove only | 10 μm to 20 μm |
| First and second grooves | 5μm to 10 μm |
| First, second, and third grooves | 2.5 μm to 5 μm |
| All four grooves | Less than 2.5 μm |

NOTE:
(1) Assuming the tip has a standard 90 deg apex angle (see Fig. 11-7).

B2 specimens with multiple isosceles triangular grooves with sharp peaks and valleys may be used for estimating the radii of stylus tips (see Fig. 11-6). As the tip size increases, the measured roughness average $R_a$ decreases for this type of specimen.

For testing 10 μm radius tips, a useful B2 specimen design has $\alpha$ = 150 deg and an *ideal* $R_a$ of 0.5 μm ± 5% (i.e., measured with a stylus with radius much finer than 10 μm). The mean peak spacing $S_m$ thus has a value of approximately 15 μm.

NOTE: To assess the calibrated value of the B2 specimen, at least 18 evenly distributed traces shall be taken on each specimen, all instrument adjustments remaining constant throughout the determination. The stylus tip radius used to perform the assessment must be previously measured, for example using a Type B3 specimen.

The Type B3 specimen is a fine protruding edge. Uncoated razor blades have tip widths of approximately 0.1 μm or less. The stylus condition may be accurately measured by traversing such a specimen as shown in Fig. 11-7. If $r_1$ is the stylus tip radius and $r_2$ is the radius of the razor blade edge, the recorded profile has a radius $r = r_1 + r_2$. If, in addition, $r_2$ is much less than $r_1$, then the recorded radius is approximately equal to the stylus tip radius itself. This method can only be used with direct profile recording instruments with very slow traversing speed capability.

### 11.7.3 Types C1, C2, C3, and C4

NOTE: The nominal values given in Tables 11-5, 11-7, and 11-8 are values that assume negligible attenuation by the stylus or filter.

Type C1: Grooves having a sine wave profile (see Fig. 11-8). See Table 11-5 for recommended values of $R_a$ and $S_m$ for these specimens as well as the recommended values of cutoff to use when measuring them. For tolerances and uncertainties, see Table 11-6.

Type C2: Grooves having an isosceles triangle profile (see Fig. 11-6). See Table 11-7 for nominal values of $R_a$ and $S_m$. For tolerances, see Table 11-6.

Type C3: Simulated sine wave grooves include triangular profiles with rounded or truncated peaks and valleys (see Fig. 11-9), the total rms harmonic content of which shall not exceed 10% of the rms value of the fundamental. Recommended values of $R_a$ and $S_m$ are the same as those shown for Type C2 specimens in Table 11-7. For tolerances, see Table 11-6.

Type C4: Grooves having an arcuate profile (see Fig. 11-10). For recommended values of $R_a$ and $S_m$, see Table 11-8. For tolerances, see Table 11-6.

**11.7.4 Type D.** These specimens have an irregular ground profile which is repeated every evaluation length in the longitudinal direction of the specimen. The grooves on the measuring area have a constant profile, i.e., the surface is essentially smooth along the direction perpendicular to the direction of measurement (see Fig. 11-11).

The nominal $R_a$ values of the specimens may range from 0.01 μm to 1.5 μm. For tolerances of certain higher $R_a$ values in this range, see Table 11-9. Recommended tolerances for the smaller $R_a$ values have not yet been determined.

### 11.8 Marking

After each specimen has been individually calibrated, it shall be accompanied by the following statements as applicable:

(*a*) type(s) of specimen;
(*b*) the nominal value;
(*c*) the effective radius of the stylus tip(s) to which each calibrated value applies;
(*d*) the type of filter and cutoff;
(*e*) details of calibration:
(*1*) for Types A1 and A2, the calibrated mean value of the depth of the groove, the standard deviation from the mean, and the number of evenly distributed observations taken;

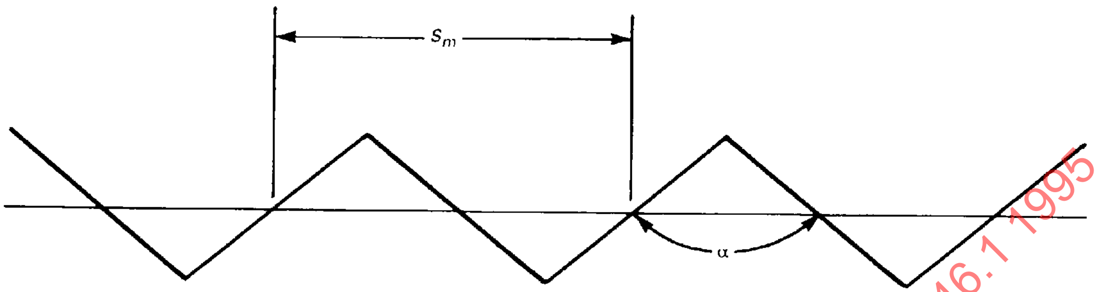
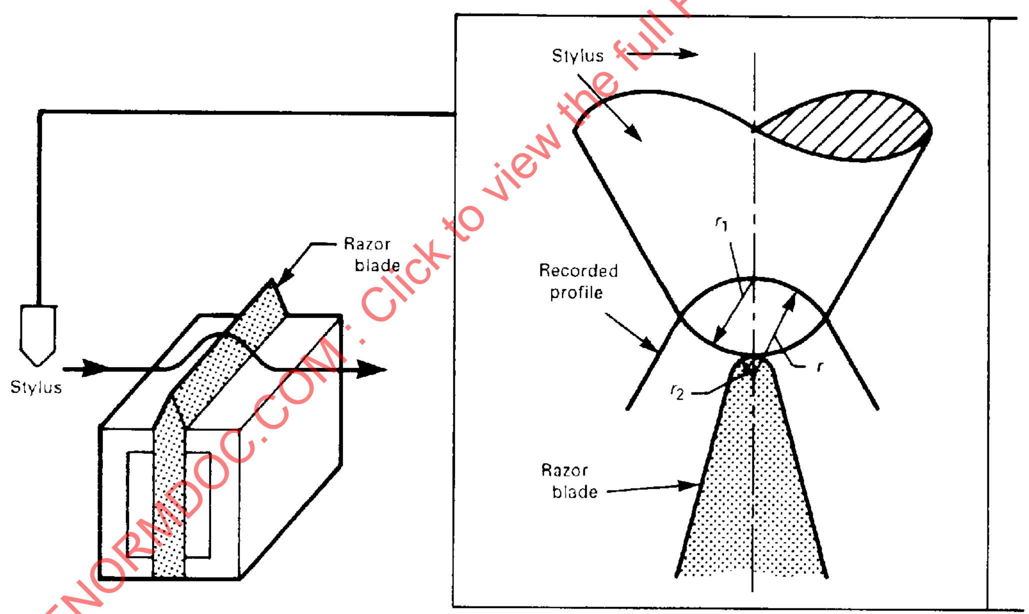



FIG. 11-6 TYPE B2 OR C2 SPECIMENS WITH MULTIPLE GROOVES






GENERAL NOTES:
(a) Schematic diagram of razor blade trace for profiling the shape of a stylus tip to determine its radius.
(b) The output profile essentially represents the stylus tip shape if the radius and apex angle of the razor blade are much finer.
(c) See E.C. Teague, *NBS Tech. Note* 902 (1976) and J.F. Song and T.V. Vorburger, *Applied Optics* 30 (1990):42.

FIG. 11-7 USE OF TYPE B3 SPECIMEN

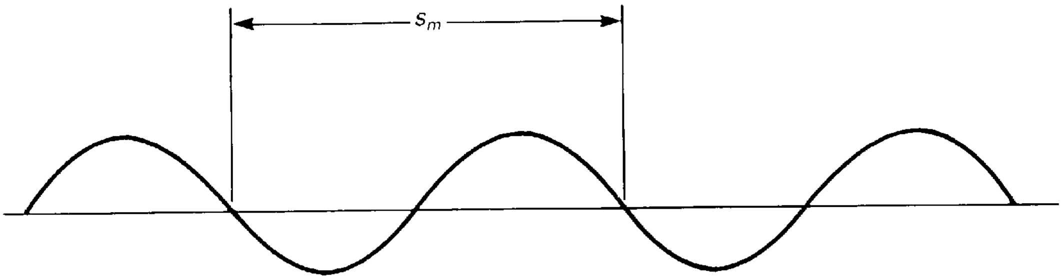



**FIG. 11-8 TYPE C1 GROOVES**

(2) for Type B2, the estimated mean $R_a$ value for a probe tip of specified radius;

(3) for Types C and D, the calibrated mean value of $R_a$ for each tip used, the value and type of filter for which the specimen may be used, the standard deviation from each mean, and the number of observations taken.

(f) the permitted uncertainty in the calibrated mean values as given in Tables 11-3, 11-6, or 11-9;

(g) any other reference conditions to which each calibration applies, for example the least significant bits of digital evaluation, and whether the declared values refer to direct measurement or are derived from surface models.

### TABLE 11-5 RECOMMENDED $R_a$ AND $S_m$ VALUES FOR TYPE C1 SPECIMENS

| Mean Spacing of Profile Irregularities $S_m$, mm | Selected Cutoffs (mm) To Check $R_a$ | $R_a$, µm | | |
|---|---|---|---|---|
| 0.01 | 0.08 | 0.1 | 0.3 | 1 |
| 0.03 | 0.25 | 0.3 | 1 | 3 |
| 0.1 | 0.8 | 1 | 3 | 10 |
| 0.3 | 2.5 | 3 | 10 | 30 |

GENERAL NOTE: The nominal values given assume negligible attenuation by the stylus or filter.

### TABLE 11-6 TOLERANCES FOR TYPES C1 TO C4

| Nominal Value of $R_a$, µm | Tolerance on Nominal Value, % | Uncertainty of Measurement of Stated Mean Value of $R_a$, % | Standard Deviation from Mean Value, % |
|---|---|---|---|
| 0.1 | ±25 | ±3 | 3 |
| 0.3 | ±20 | ±2 | 2 |
| 1 | ±15 | ±2 | 2 |
| 3 | ±10 | ±2 | 2 |
| 10 | ±10 | ±2 | 2 |



### TABLE 11-7 NOMINAL VALUES OF $R_a$ AND $S_m$ FOR TYPE C2

| Mean Spacing of Profile Irregularities, $S_m$, mm | | | | | |
|---|---|---|---|---|---|
| 0.08 | 0.1 | 0.25<br>$R_a$, µm | 0.8 | 2.5 | α, deg |
| 0.1 | | 0.3 | 1.0 | 3.0 | 179 |
| 0.3 | | 1.0 | 3.0 | 10.0 | 176 |
| 1.0 | | 3.0 | 10.0 | 30.0 | 169 |
| 3.0 | | 10.0 | 30.0 | | 145 |
| | 3.0 | | | | 153 |

GENERAL NOTE: The nominal values given assume negligible attenuation by the stylus or filter.

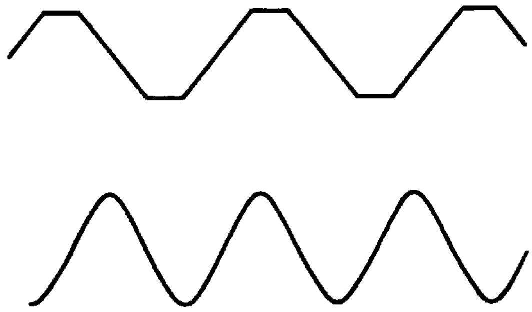


**FIG. 11-9 TYPE C3 GROOVES**

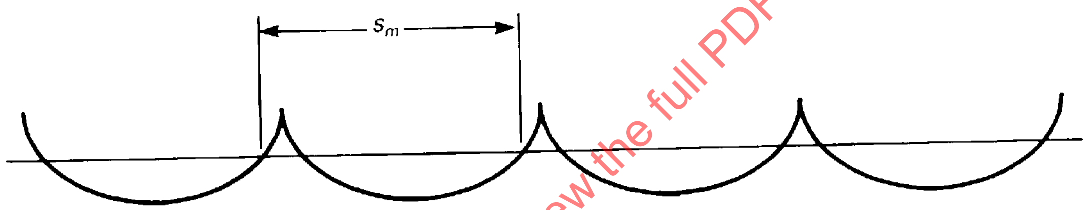
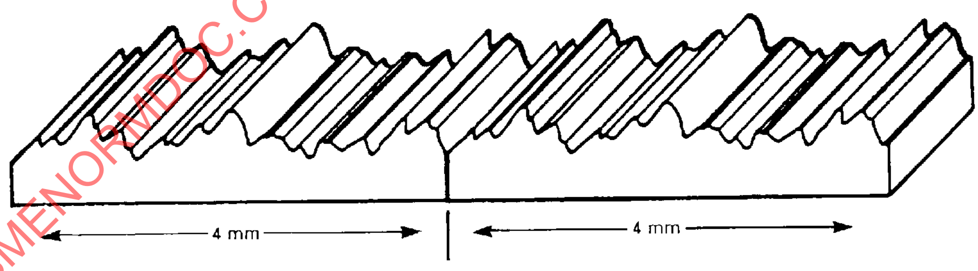



**FIG. 11-10 TYPE C4 GROOVES**




GENERAL NOTE: Profile repetition at 4 mm intervals.

**FIG. 11-11 UNIDIRECTIONAL IRREGULAR GROOVES**

**TABLE 11-8 NOMINAL VALUES OF $R_a$ FOR TYPE C4 [NOTE (1)]**

| Mean Spacing of Profile Irregularities $S_m$, mm [Note (2)] | $R_a$, μm | | | |
|---|---|---|---|---|
| 0.25 | 0.2 | 3.2 | 6.3 | 12.5 |
| 0.8 | 3.2 | 6.3 | 12.5 | 25.0 |

NOTES:
(1) Neglecting any attenuation by the filter.
(2) The filter cutoff $\lambda_c$ must be at least 5 times the $S_m$ values shown here.



**TABLE 11-9 TOLERANCES FOR UNIDIRECTIONAL IRREGULAR PROFILES [NOTE (1)]**

| Nominal Value of $R_a$, μm | Tolerance on Nominal Value, % | Uncertainty of Measurement of Stated Mean Value of $R_a$ [Note (2)], % | Standard Deviation from Mean Value, % |
|---|---|---|---|
| 0.15 | ±30 | ±5 | 4 |
| 0.5 | ±20 | ±3 | 3 |
| 1.5 | ±15 | ±3 | 3 |

NOTES:
(1) $\lambda_c$ = 0.8 mm
(2) Taken from 12 evenly distributed readings.

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# SECTION 12 SPECIFICATIONS AND PROCEDURES FOR ROUGHNESS COMPARISON SPECIMENS

## 12.1 Scope of Section 12

This Section specifies the characteristics of specimens which are intended for comparison with workpiece surfaces of similar lay and produced by similar manufacturing methods. These comparisons may be performed by area averaging techniques as discussed in Section 6 or by the visual/tactile approach.

## 12.2 References

Section 1, Terms Related to Surface Texture

Section 2, Classification of Instruments for Surface Texture Measurement

Section 6, Measurement Techniques for Area Averaging

## 12.3 Definitions

*roughness comparison specimen* — a specimen surface with a known surface roughness parameter representing a particular machining or other production process

Other definitions of terms are given in Section 1.

## 12.4 Roughness Comparison Specimens

Roughness comparison specimens are used to guide design personnel with respect to the feel and appearance of a surface of known roughness grade produced by a selected process. The roughness comparison specimens are intended to assist workshop personnel in evaluating and controlling the surface topography of the workpieces by comparing them with the specimen surface. At least one surface parameter must be marked on the specimen (conventionally $R_a$). Additional parameters to describe the surface of the specimen could also be added. Roughness comparison specimens are not suitable for the calibration of surface measuring instruments.

**12.4.1 Individually Manufactured (Pilot) Specimens.** These specimens are made by direct application of the production process the specimen is intended to represent.

**12.4.2 Replica Specimens.** These specimens are positive replicas of master surfaces. They may be electroformed or made of plastic or other materials and coated or otherwise treated to have the feel and appearance of the surfaces produced directly by a selected manufacturing process.

## 12.5 Surface Characteristics

Individually manufactured specimens, master surfaces for reproduction, and their replicas shall exhibit only the characteristics resulting from the natural action of the production process they represent. They shall not contain surface irregularities produced by abnormal conditions such as vibrations, etc.

## 12.6 Nominal Roughness Grades

Nominal roughness grades for comparison specimens shall be from the series in Table 12-1.

Nominal roughness average ($R_a$) grades for various manufacturing processes are listed in Table 12-2 along with corresponding sampling lengths.

## 12.7 Specimen Size, Form, and Lay

Comparison specimens shall be of adequate size to permit initial calibration and periodic verification. For specimen surfaces having nominal $R_a$ values of 6.3 $\mu$m or less, no side should be less than 20 mm. For the $R_a$ value 12.5 $\mu$m, no side should be less than 30 mm. For $R_a$ values greater than 12.5 $\mu$m, no side should be less than 50 mm. The general direction of the lay should be parallel to the shorter side of the specimen. In cases such as fine peripheral milling, when the surface irregularities resulting

### TABLE 12-1 NOMINAL ROUGHNESS GRADES ($R_a$) FOR ROUGHNESS COMPARISON SPECIMENS

| μm | μin. |
|---|---|
| 0.006 | 0.25 |
| 0.0125 | 0.5 |
| 0.025 | 1 |
| 0.05 | 2 |
| 0.1 | 4 |
| 0.2 | 8 |
| 0.4 | 16 |
| 0.8 | 32 |
| 1.6 | 63 |
| 3.2 | 125 |
| 6.3 | 250 |
| 12.5 | 500 |
| 25 | 1,000 |
| 50 | 2,000 |
| 100 | 4,000 |
| 200 | 8,000 |
| 400 | 16,000 |



### TABLE 12-2 FORM AND LAY OF ROUGHNESS COMPARISON SPECIMENS REPRESENTING VARIOUS TYPES OF MACHINED SURFACES

| Process Represented | Form of Specimen | Lay |
|---|---|---|
| Peripheral OD Grinding | Convex Cylindrical | Uniaxial |
| ID Grinding | Concave Cylindrical | Uniaxial |
| Peripheral Flat Grinding | Flat | Uniaxial |
| Side-Wheel Grinding | Flat | Crossed Arcuate |
| Cup-Wheel Grinding | Flat | Crossed Arcuate |
| OD Turning | Convex Cylindrical | Uniaxial |
| ID Turning | Concave Cylindrical | Uniaxial |
| Face Turning | Flat | Circular |
| Peripheral Milling | Flat | Uniaxial |
| End Milling | Flat | Arcuate, Crossed Arcuate |
| Boring | Concave Cylindrical | Uniaxial |
| Shaping | Flat | Uniaxial |
| Planing | Flat | Uniaxial |
| Spark Erosion | Flat | Nondirectional |
| Shot or Grit-Blasting | Flat | Nondirectional |
| Polishing | Flat, Convex Cylindrical | Multidirectional |

from imperfection of cutting edges appear to be of greater consequence than the surface irregularities resulting from cutter feed, the dominant lay should be parallel to the shorter side of the specimen although the feed marks may be parallel to the longer side. The form and lay of standard comparison specimens representing machined surfaces shall be as shown in Table 12-2.

### 12.8 Calibration of Comparison Specimens

Specimens are to be evaluated using an instrument capable of measuring parameters in accordance with this Standard. The sampling lengths are given in Table 12-3. For periodic profiles, use Table 3-1, Section 3. The evaluation length shall include at least five sampling lengths. A sufficient number of readings across the lay of the surface shall be taken at evenly distributed locations (at least 5) to enable the mean value of selected surface parameters to be determined with a standard deviation of the mean of 10% or less. The mean value of the readings shall be between 83% and 112% of the nominal value.

### 12.9 Marking

Markings shall not be applied to the reference surface of the specimen. The mounting of the specimen shall be marked with at least the following:

(*a*) the expression *nominal* $R_a$, the nominal and measured $R_a$ values in $\mu$m or $\mu$in., and the unit of measurement ($\mu$m or $\mu$in.);

(*b*) the production process represented by the specimen (e.g., ground, turned);

(*c*) the designation, *comparison specimen*.

Optionally, roughness parameters other than $R_a$ may be added.

## TABLE 12-3 SAMPLING LENGTHS FOR CALIBRATION OF COMPARISON SPECIMENS, mm

| Type of Surface | Nom. $R_a$, μm | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.006 | 0.0125 | 0.025 | 0.05 | 0.1 | 0.2 | 0.4 | 0.8 | 1.6 | 3.2 | 6.3 | 12.5 | 25 | 50 | 100 | 200 | 400 |
| **Machined Surfaces:** | | | | | | | | | | | | | | | | | |
| Polished | 0.08 | 0.08 | 0.08 | 0.25 | 0.25 | 0.8 | — | — | — | — | — | — | — | — | — | — | — |
| Honed | — | — | 0.25 | 0.25 | 0.25 | 0.8 | 0.8 | 0.8 | 0.8 | — | — | — | — | — | — | — | — |
| Ground | — | — | 0.25 | 0.25 | 0.25 | 0.25 | 0.8 | 0.8 | 0.8 | 2.5 | — | — | — | — | — | — | — |
| Shot Blasted | — | — | — | — | — | 0.8 | 0.8 | 0.8 | 0.8 | 2.5 | 2.5 | 2.5 | 2.5 | — | — | — | — |
| Grit Blasted | — | — | — | — | — | 0.8 | 0.8 | 0.8 | 0.8 | 2.5 | 2.5 | 2.5 | 2.5 | — | — | — | — |
| Turned | — | — | — | — | — | — | [Note (1)] | [Note (1)] | [Note (1)] | [Note (1)] | [Note (1)] | [Note (1)] | — | — | — | — | — |
| Bored | — | — | — | — | — | — | [Note (1)] | [Note (1)] | [Note (1)] | [Note (1)] | [Note (1)] | [Note (1)] | — | — | — | — | — |
| Milled | — | — | — | — | — | — | [Note (1)] | [Note (1)] | [Note (1)] | [Note (1)] | [Note (1)] | [Note (1)] | — | — | — | — | — |
| Shaped | — | — | — | — | — | — | — | [Note (1)] | [Note (1)] | [Note (1)] | [Note (1)] | [Note (1)] | [Note (1)] | — | — | — | — |
| Planed | — | — | — | — | — | — | — | [Note (1)] | [Note (1)] | [Note (1)] | [Note (1)] | [Note (1)] | [Note (1)] | — | — | — | — |
| Spark Eroded | — | — | — | — | — | — | 0.8 | 0.8 | 0.8 | 2.5 | 2.5 | 2.5 | — | — | — | — | — |
| **Cast Surfaces:** | | | | | | | | | | | | | | | | | |
| *Steel* | | | | | | | | | | | | | | | | | |
| Precision Cast | — | — | — | — | — | — | — | 0.8 | 0.8 | 2.5 | 2.5 | 2.5 | — | — | — | — | — |
| Shell Molded | — | — | — | — | — | — | — | — | 0.8 | 2.5 | 2.5 | 2.5 | 2.5 | 8.0 | — | — | — |
| Sand Cast | — | — | — | — | — | — | — | — | — | — | — | 2.5 | 2.5 | 8.0 | 8.0 | 25.0 | 25.0 |
| *Iron* | | | | | | | | | | | | | | | | | |
| Shell Molded | — | — | — | — | — | — | — | — | 0.8 | 2.5 | 2.5 | 2.5 | 2.5 | — | — | — | — |
| Sand Cast | — | — | — | — | — | — | — | — | — | 2.5 | 2.5 | 2.5 | 2.5 | 8.0 | 8.0 | 25.0 | — |
| *Aluminum Alloy* | | | | | | | | | | | | | | | | | |
| Pressure Die Cast | — | — | — | — | — | — | 0.8 | 0.8 | 0.8 | 2.5 | 2.5 | 2.5 | 2.5 | 8.0 | — | — | — |
| Gravity Die Cast | — | — | — | — | — | — | — | 0.8 | 0.8 | 2.5 | 2.5 | 2.5 | 2.5 | 8.0 | — | — | — |
| Sand Cast | — | — | — | — | — | — | — | — | — | 2.5 | 2.5 | 2.5 | 2.5 | 8.0 | 8.0 | 25.0 | — |
| *Copper Alloy* | | | | | | | | | | | | | | | | | |
| Pressure Die Cast | — | — | — | — | — | — | — | — | 0.8 | 2.5 | 2.5 | 2.5 | 2.5 | 8.0 | — | — | — |
| Gravity Die Cast | — | — | — | — | — | — | — | — | — | 2.5 | 2.5 | 2.5 | 2.5 | 8.0 | 8.0 | — | — |
| Sand Cast | — | — | — | — | — | — | — | — | — | — | 2.5 | 2.5 | 2.5 | 8.0 | 8.0 | — | — |
| *Mg and Zn Alloys* | | | | | | | | | | | | | | | | | |
| Pressure Die Cast | — | — | — | — | — | 0.25 | 0.8 | 0.8 | 0.8 | 2.5 | 2.5 | 2.5 | 2.5 | — | — | — | — |
| Sand Cast | — | — | — | — | — | — | — | — | — | 2.5 | 2.5 | 2.5 | 2.5 | 8.0 | 8.0 | 25.0 | — |

NOTE:
(1) Refer to Section 3, Table 3-1.

# APPENDIX A

## GENERAL NOTES ON USE AND INTERPRETATION OF DATA PRODUCED BY STYLUS INSTRUMENTS

(This Appendix is not part of ASME B46.1-1995 and is included for information only.)



**A1** Most surfaces of engineering interest are complex, generally consisting of randomly distributed irregularities characterized by a wide range of height and spacing. Each surface characterization parameter relates to a selected topographical feature of the surface of interest.

**A2** One useful quantity in characterizing a surface is the roughness average $R_a$, as described in Section 1 of ASME B46.1. A common method of measuring the roughness average uses the motion of a sharp-pointed stylus over the surface and the conversion of the displacement normal to the surface into an output reading proportional to the roughness average. A number of factors affect the results, and ASME B46.1 has attempted to specify enough of those factors so that instruments of different design and construction might yield similar values for $R_a$ that are in reasonable agreement on any given surface.

**A3** The stylus dimensions limit the minimum size of the irregularities which are included in a measurement. The specified value of stylus tip radius has been chosen to be as small as practical to include the effect of fine irregularities. Stylus radii ranging between 1 and 10 $\mu$m are fairly common. Since styli of such small radius are subject to wear and mechanical damage even when made of wear-resistant materials, it is recommended that frequent checks of the stylus be made to ensure that the tip radius does not exceed the specified value.

**A4** One means of providing a reference surface against which to measure stylus movement is to support the tracer containing the stylus on skids, the radii of which are large compared to the height and spacing of the irregularities being measured. In measuring surface roughness in small holes, slots, and recesses, and on short shoulders, gear teeth, and thread surfaces, the geometry may not permit the use of skids to support the tracer. In such cases, the tracer body is supported and moved over a reference datum, and the tracer stylus is mounted at the end of a suitable beam.

**A5** Since most surfaces are not uniform, fluctuations in instantaneous average readings will occur. Therefore, the correct average reading will not be reached instantaneously. In using an instrument, a sufficient length of surface must be traversed to ensure that the full reading characteristic of the surface is obtained. This length depends upon the cutoff selected. The roughness reading may also vary with location of the sampled profile on the surface. In most common machining processes it is generally possible to obtain adequate surface finish control with three measurements. If the process used produces parts that vary widely in roughness average $R_a$ over the surface, the use of a statistical average of a number of measurements may be desirable. This statistical averaging procedure must be clearly defined in the surface specifications, and cannot be inferred by stated compliance with ASME B46.1.

**A6** In general, surfaces contain irregularities characterized by a large range of widths. Instruments are designed to respond only to irregularity spacings less than a given value, called the cutoff. In some cases, such as a surface whose actual contact area with a mating surface is important, a large cutoff value might be selected. In other cases, such as surfaces subject to fatigue failure, irregularities of small width tend to be important, and more significant values will be obtained when a small cutoff value is used. In still other cases, such as identifying chatter marks on machined surfaces, information is needed on only the widely spaced irregularities. A large cutoff value and a large radius stylus may then be specified and used to inhibit the instrument response to the more closely spaced irregularities.

**A7** Three methods are discussed in ASME B46.1 for separating the roughness and waviness aspects of the surface (by Gaussian filtering, by 2RC filtering, or by segmentation of the profile into roughness sampling lengths). These methods treat a profile in different ways so that slightly different $R_a$ values may be obtained. The numerical difference between values obtained from methods of measurement that produce values which are nominally but not precisely equal is referred to as *methods divergence*. The methods divergence arises here because the methods use different center lines and yield different attenuation rates for profile spatial wavelengths near the cutoff or roughness sampling length. The center line for instruments using a cutoff filter is a wavy one, generally following the shape of the larger irregularities of the profile. In the segmentation procedure, the center line is composed of straight line segments, each having a length equal to the roughness sampling length. The attenuation rates for Gaussian filters specified in Section 9 of ASME B46.1 are such that a sinusoidal waveform with a spatial wavelength equal to the cutoff would be attenuated by 50%. For the 2RC filter, the attenuation at the cutoff is only 25%. In the segmentation procedure, even less attenuation occurs at the cutoff spatial wavelength. For spatial wavelengths greater than the cutoff or sampling length, the effective attenuation rates of the three procedures differ. For surfaces produced by most material removal processes, the methods divergence for $R_a$ measurements is usually small. In some instances the divergence may be as much as 10%. See the recommendation in Section 2 of ASME B46.1 to handle cases when the differences obtained by different methods are significant.

# APPENDIX B
# CONTROL AND PRODUCTION OF SURFACE TEXTURE

(This Appendix is not part of ASME B46.1-1995 and is included for information only.)



## B1 SPECIFICATION

(*a*) Surface texture should not be controlled on a drawing or specification unless such control is essential to the functional performance or appearance of the product. Unnecessary restrictions may increase production costs and will mitigate the emphasis on specifications for important surfaces.

(*b*) In the mechanical field, many surfaces do not require any control of surface texture beyond that required to obtain the necessary dimensions on the manufactured component.

(*c*) Working surfaces such as those on bearings, pistons, and gears are typical of surfaces that require control of the surface characteristics to perform optimally. Control may be achieved if the procedures outlined in ASME B46.1 are followed. Nonworking surfaces such as those on the walls of transmission cases, crankcases, or housings seldom require any surface texture control.

(*d*) Experimentation or experience with surfaces performing similar functions is the best criterion on which to base selection of optimum surface characteristics. Determination of required characteristics for working surfaces may involve consideration of such conditions as the area of contact, the load, speed, direction of motion, type and amount of lubricant, temperature, and material and physical characteristics of component parts. Variations in any one of the conditions may require changes in the specified surface characteristics.

## B2 PRODUCTION

(*a*) Surface texture is a result of the processing method. Surfaces obtained from casting, forging, or burnishing have undergone some plastic deformation. For surfaces that are machined, ground, lapped, or honed, the texture is the result of the action of cutting tools, abrasives, or other forces. It is important to understand that surfaces with similar roughness average ratings may not have the same performance, due to tempering, subsurface effects, different profile characteristics, etc.

(*b*) Figure B1 shows the typical range of surface roughness values which may be produced by common production methods. The ability of a processing operation to produce a specific surface roughness depends on many factors. For example, in surface grinding, the final surface depends on the peripheral speed of the wheel, the speed of the traverse, the rate of feed, the grit size, bonding material and state of dress of the wheel, the amount and type of lubrication at the point of cutting, and the mechanical properties of the piece being ground. A small change in any of the above factors may have a marked effect on the surface produced.

## B3 INSPECTION

(*a*) ASME B46.1 explains the interpretation of specifications of surface finish on drawings. Although ASME B46.1 permits considerable latitude in the method of producing and inspecting a surface, it specifies limits on the characteristics of measuring instruments, roughness comparison specimens, and precision reference specimens. These specifications are essential for the reliable measurement of surface parameters and are thus necessary for establishing and maintaining control of surface texture. The roughness comparison specimens allow engineers or designers to obtain an approximate idea of the surface textures produced by various machining processes. The instruments permit the accurate measurement of characterization parameters for surfaces generated in production. The precision reference

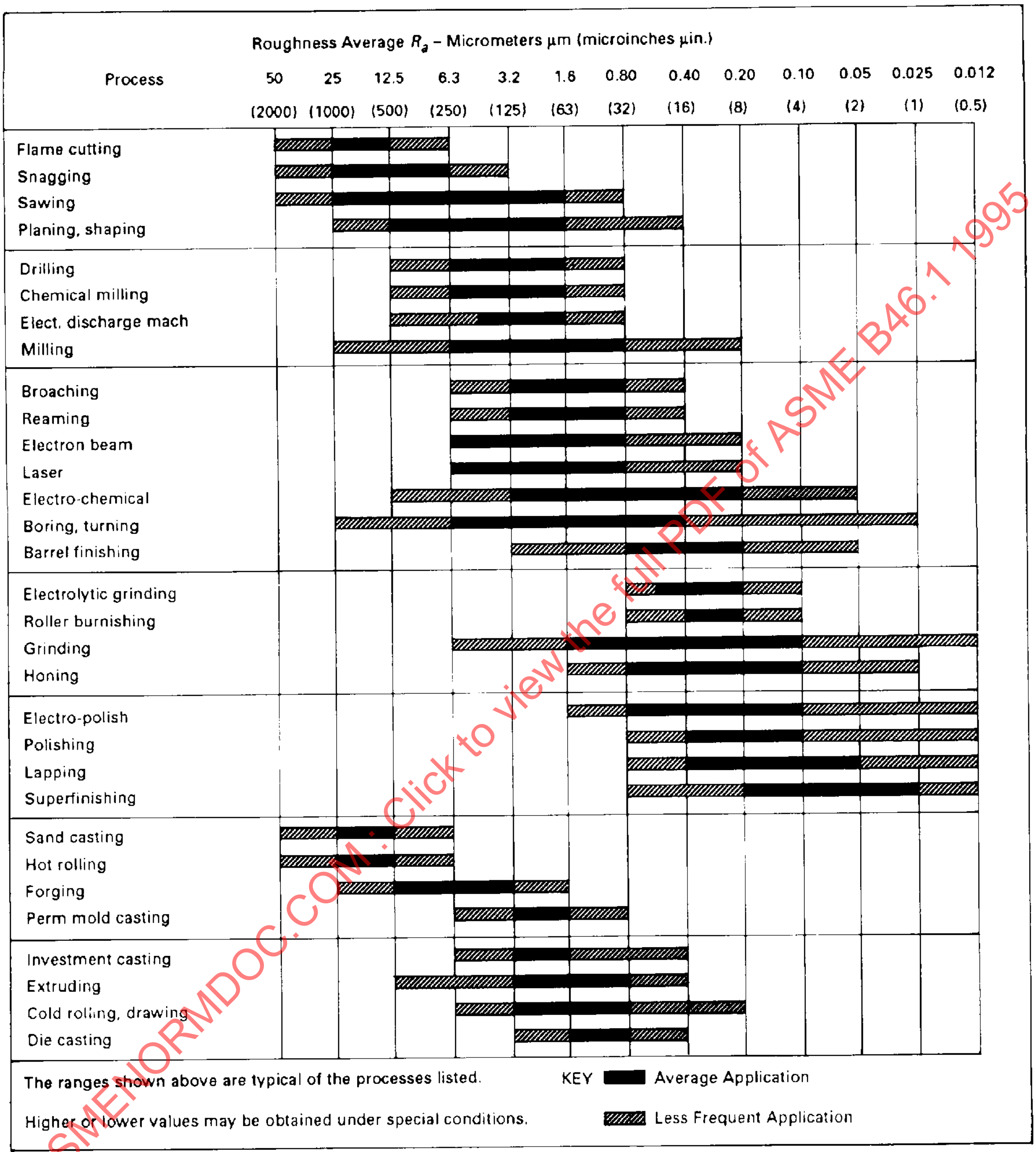




**FIG. B1 SURFACE ROUGHNESS PRODUCED BY COMMON PRODUCTION METHODS**

specimens provide an accurate means of calibrating the measuring instruments.

(*b*) One of the methods of control and inspection covered in ASME B46.1 is the use of pilot specimens which are actual piece parts from the production setup that conform to the surface requirements specified on the drawing. To assure reasonable accuracy, pilot specimens should be rated by calibrated measuring instruments. Pilot specimens may be used to control production operations by sight and feel. Because these pilot specimens are of the same size, shape, material, and physical characteristics as production parts from the same machine setup, it is often possible to determine by sight or feel when production parts begin to deviate significantly from the established norm indicated by the pilot specimen. If control is required at more than one station, pilot specimens may be cut into the required number of pieces. Electroformed or plastic replicas of the pilot specimens may also be satisfactory.

(*c*) Visual aids and comparator instruments, other than those of the stylus type, are sometimes useful for comparing the work pieces with pilot specimens or roughness comparison specimens. However, the use of roughness comparison specimens or replicas of pilot specimens for visual inspection, requires the adoption of precautions to assure the accuracy of observation. Optical reflectivity is not necessarily a reliable index of roughness, since it is dependent on such factors as the specular properties of the material, the lighting conditions, viewing angle, roughness width, and color, as well as roughness height.

## B4 SURFACE TEXTURE OF CASTINGS

(*a*) Surface characteristics of castings should not be considered on the same basis as machined surfaces. Castings are characterized by random distribution of nondirectional deviations from the nominal surface.

(*b*) Surfaces of castings rarely need control beyond that provided by the production method necessary to meet dimensional requirements. Comparison specimens are frequently used for evaluating surfaces having specific functional requirements. Surface texture control should not be specified unless required for appearance or function of the surface. Specification of such requirements may increase the cost to the user.

(*c*) Engineers should recognize that different areas of the same castings may have different surface textures. It is recommended that specifications of the surface be limited to defined areas of the casting. The practicality and the methods of determining that a casting's surface texture meets the specification should be coordinated with the producer. The Society of Automotive Engineers Standard J435C, Automotive Steel Castings, describes methods of evaluation for steel casting surface texture used in the automotive and related industries.

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# APPENDIX C
# A REVIEW OF ADDITIONAL SURFACE MEASUREMENT METHODS

(This Appendix is not part of ASME B46.1-1995 and is included for information only. See also Appendices E and F for other commonly used methods.)



## C1 INTRODUCTION

(*a*) This Appendix highlights certain surface measurement techniques other than those described in ASME B46.1.

(*b*) The large number of surface examination methods (including the different characteristics of probes) and the wide variety of data analysis techniques preclude complete agreement of results obtained by different techniques. However, methods divergence need not prevent a unified approach to surface measurement agreed upon by buyer and seller, which forms a suitable basis for necessary agreement between them, as well as between engineering and manufacturing activities, between industry groups, and between the US and foreign countries.

(*c*) Surface texture, in the sense of ASME B46.1, is generally only one of the essential elements for surface description and control. Additional surface quality information can usually be obtained from other types of instrumentation and analysis such as:

(*1*) optics, including microscopy, reflectance measurement, image analysis, and holography;

(*2*) electron optics (both scanning and transmission electron microscopy);

(*3*) nondestructive testing methods including ultrasonics, eddy current, and capacitance;

(*4*) precision dimensional engineering measurement including air gauging and measurement of form;

(*5*) surface integrity measurements (see para. C5, [1]) of hardness changes, stress, fatigue, and deterioration resulting from machining processes that cause altered zones of material at and immediately below the surface. Component integrity may depend significantly on these types of surface properties;

(*6*) chemical characterization including electron and ion spectroscopy and analysis.

## C2 OPTICAL METHODS

### C2.1 Introduction

Optical microscopes have spatial resolution capabilities limited by the following criteria.

(*a*) For spatial resolution, the generally accepted Rayleigh criterion states that two objects in the focal plane of a diffraction limited lens will be resolved when they are separated by more than a distance $d$ as stated in the formula:

$$d = \frac{k\lambda_o}{NA}$$

where

$k$ = constant between 0.6 and 0.8 depending on the shape of the object and illumination
$\lambda_o$ = wavelength of the illumination
$NA$ = numerical aperture of the lens

(*b*) The numerical aperture $NA$ is a function of the refractive index of the medium between the lens and the object, usually air, and the angle subtended at the object plane by the effective radius of the lens. Typical microscope lenses have $NA$ values from 0.2 to 0.9. The larger value may be extended to 1.4 by using immersion techniques.

(*c*) The highest useful magnification for which valid information may be obtained is discussed in the following descriptions of instruments. The range of useful magnification available depends largely on the differences in numerical aperture between instruments.

### C2.2 Light Section Microscopy

(*a*) An oblique thin sheet of light or a projected line image provides an outline of irregularities on the specimen surface. This approach was first mentioned by Schmaltz (see para. C5, [2]) in 1931 and has since been refined and modified by a number of designers.

(*b*) The Schmaltz instrument uses two objective lenses oriented at approximately 45 deg to the surface normal. One lens transmits a thin sheet of light onto the surface and the other lens is used to observe the profile that is produced. The method is generally limited to 400× magnification with a spatial resolution of about 1 $\mu$m (40 $\mu$in.) (see Fig. C1).

(*c*) Light section microscopes can provide a three-dimensional effect when the specimen is slowly moved past the instrument. In addition to their use as surface profile instruments, they can be used to measure step heights, flatness, and parallelism of surfaces. They can also be equipped with an auxiliary measuring system and used as a noncontacting null sensor.

### C2.3 Optical Reflectance Measurement (Glossmeters)

(*a*) Relative measurements can be made by beaming either single or multiple wavelengths obliquely at the tested surface and measuring the ratios of specular to scattered intensities. Glossmeters operate on this principle (see para. C5, [3] and Fig. C2).

### C2.4 Double Beam Interferometry: Circular Path Profiler

The circular path profiler developed by Sommargren (para. C5, [4] and [5]), is shown in Fig. C3. Two laser beams (with different polarization states) are separated by a Wollaston prism and are incident on a surface. The relative height of the two points of illumination is measured by sensing the relative phase of the reflected beams. The measured sample is then rotated. One of the beams serves as a reference because it illuminates the stationary point on the surface on the axis of rotation. The other beam then serves to measure a surface height profile of the circular path traced over the rotating surface with respect to the central reference point.

### C2.5 Multiple Beam Interferometry

(*a*) In this method, pioneered by Tolansky (see para. C5, [6]), the side of the reference flat facing

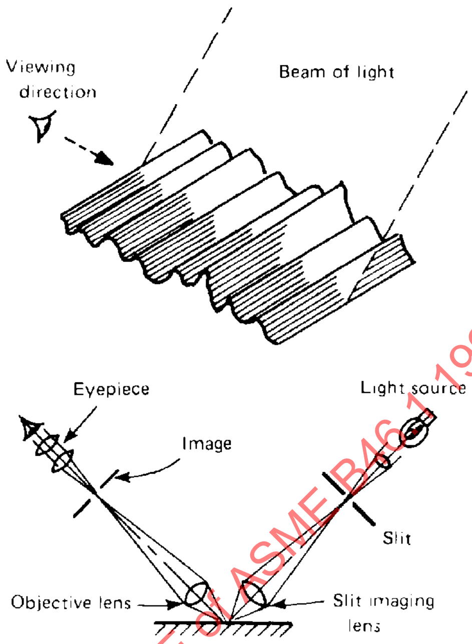


FIG. C1 SCHMALTZ PROFILE MICROSCOPE

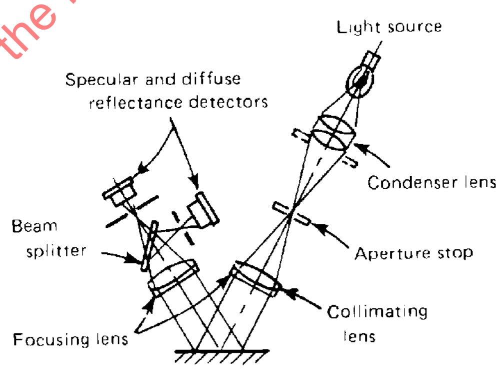


FIG. C2 REFLECTANCE MEASUREMENT

the workpiece has to be coated with a thin semi-reflecting film having low absorption and a reflectivity approximately matching that of the workpiece (see Fig. C4).

(*b*) If the distance between the surfaces is small enough, of the order of a few wavelengths of light,

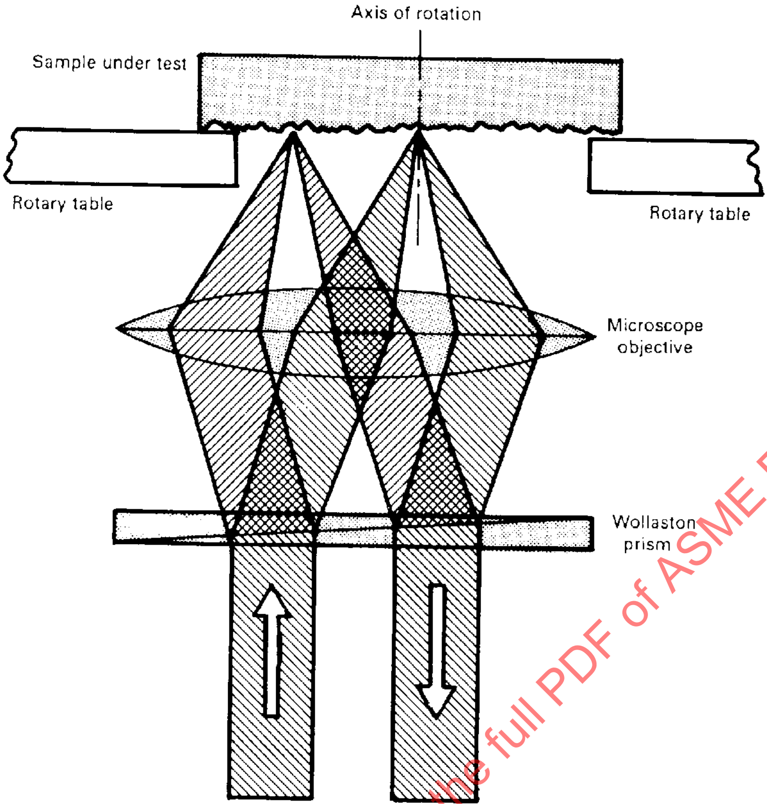


FIG. C3 SCHEMATIC DIAGRAM OF CIRCULAR PATH PROFILER

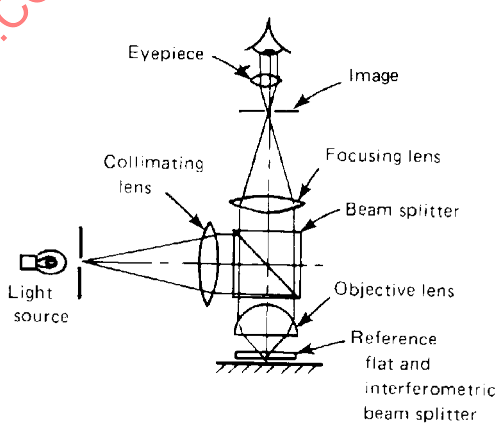


FIG. C4 MULTIPLE BEAM INTERFEROMETER

the light will be reflected back and forth many times between the two surfaces. Extremely sharp fringes result, which are easier to interpret than the broader appearing fringes from a double-beam interferometer. The practical upper limit of magnification is approximately 125× to 150×. Monochromatic light is essential and good fringe sharpness and contrast depend on high reflectivity and low absorption for the workpiece and reference mirror. Because of the close spacing between the workpiece and the reference mirror, the coating on the latter can become damaged, and must be replaced periodically.

### C2.6 Differential Interference Contrast or Nomarski Microscope

This instrument (see para. C5, [7]) consists of a Wollaston prism which can be attached to most metallurgical microscopes close to the objective lens. The prism produces two images of the workpiece that are sheared with respect to each other by a small amount, usually the limit of resolution of the objective. The resulting image contains greatly enhanced surface detail. Changes of height as small as 1 nm or less can be identified. The measurement is qualitative, however. The various shades of gray in the image represent different slopes on the work surface. Differential interference contrast can be used with any magnification that is available on the microscope, although the lower magnifications show more surface detail. Figure C5 is a differential interference contrast photograph of an automobile cylinder wall before run-in.

### C2.7 Differential Interferometry

(*a*) This system is similar to differential interference contrast. However, the amount of shear of the two images is much greater, generally 20% of the field of view. The composite image is overlaid with interference fringes indicating the difference in height between the two sheared images. The fringes are of exceptionally high contrast because the workpiece is acting as its own reference mirror which, of course, has the same reflectivity. The effects of vibration between the workpiece and the microscope are cancelled because the reference mirror and workpiece are identical. The fringes are always straight regardless of the curvature of the workpiece as long as there are no discontinuities within the field of view. White light as well as monochromatic light can be used for any magnification. Precise measurements

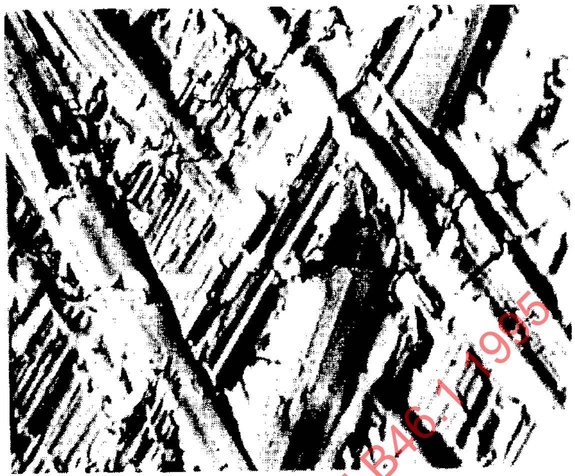

**FIG. C5 DIFFERENTIAL INTERFERENCE CONTRAST PHOTOGRAPH OF AUTOMOBILE ENGINE CYLINDER WALL**

of defect heights can be made by the usual methods of fringe interpretation as long as the steps or discontinuities are small with respect to the 20% shear of the field of view. Referring to Fig. C6, if, for instance, a simple surface has two plane surfaces, $P_1$ and $P_2$, with a step edge occurring along a straight line $AB$, it will appear in the eyepiece as two separate lines $A_1$, $B_1$, and $A_2$, $B_2$.

(*b*) The step height is evaluated as the fringe fraction:

$$\frac{a}{i} \times \frac{\lambda_o}{2}$$

where

$a$ = fringe displacement caused by the step
$i$ = spacing between adjacent fringes
$\lambda_o$ = wavelength of the illumination

(*c*) An important disadvantage of differential interferometry is that every discontinuity appears twice on the composite image. These double images are separated by the 20% shear of the field of view. If there are many discontinuities, interpretation becomes extremely difficult.