ASME B46.1-2009
(Revision of ASME B46.1-2002)

Surface Texture (Surface Roughness, Waviness, and Lay)

AN AMERICAN NATIONAL STANDARD

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AN AMERICAN NATIONAL STANDARD

Three Park Avenue • New York, NY • 10016 USA

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ASME issues written replies to inquiries concerning interpretations of technical aspects of this document. Periodically certain actions of the ASME B46 Committee may be published as Cases. Cases and interpretations are published on the ASME Web site under the Committee Pages at http://cstools.asme.org as they are issued.

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CONTENTS

Foreword		viii
Committee Roster		x
Correspondence With the B46 Committee		xi
Executive Summary		xii
Section 1	**Terms Related to Surface Texture**	1
1-1	General	1
1-2	Definitions Related to Surfaces	2
1-3	Definitions Related to the Measurement of Surface Texture by Profiling Methods	2
1-4	Definitions of Surface Parameters for Profiling Methods	7
1-5	Definitions Related to the Measurement of Surface Texture by Area Profiling and Area Averaging Methods	13
1-6	Definitions of Surface Parameters for Area Profiling and Area Averaging Methods	15
Section 2	**Classification of Instruments for Surface Texture Measurement**	19
2-1	Scope	19
2-2	Recommendation	19
2-3	Classification Scheme	19
Section 3	**Terminology and Measurement Procedures for Profiling, Contact, Skidless Instruments**	22
3-1	Scope	22
3-2	References	22
3-3	Terminology	22
3-4	Measurement Procedure	28
Section 4	**Measurement Procedures for Contact, Skidded Instruments**	29
4-1	Scope	29
4-2	References	29
4-3	Purpose	29
4-4	Instrumentation	29
Section 5	**Measurement Techniques for Area Profiling**	34
5-1	Scope	34
5-2	References	34
5-3	Recommendations	34
5-4	Imaging Methods	34
5-5	Scanning Methods	34
Section 6	**Measurement Techniques for Area Averaging**	35
6-1	Scope	35
6-2	Examples of Area Averaging Methods	35
Section 7	**Nanometer Surface Texture and Step Height Measurements by Stylus Profiling Instruments**	36
7-1	Scope	36
7-2	Applicable Documents	36
7-3	Definitions	36
7-4	Recommendations	36
7-5	Preparation for Measurement	38

7-6	Calibration Artifacts	39
7-7	Reports	39
Section 8	**Nanometer Surface Roughness as Measured With Phase Measuring Interferometric Microscopy**	41
8-1	Scope	41
8-2	Description and Definitions: Noncontact Phase Measuring Interferometer	41
8-3	Key Sources of Uncertainty	41
8-4	Noncontact Phase Measuring Interferometer Instrument Requirements	41
8-5	Test Methods	43
8-6	Measurement Procedures	43
8-7	Data Analysis and Reporting	44
8-8	References	44
Section 9	**Filtering of Surface Profiles**	45
9-1	Scope	45
9-2	References	45
9-3	Definitions and General Specifications	45
9-4	2RC Filter Specification for Roughness	46
9-5	Phase Correct Gaussian Filter for Roughness	48
9-6	Filtering for Waviness	50
9-7	Filtering of Surfaces With Stratified Functional Properties	53
Section 10	**Terminology and Procedures for Evaluation of Surface Textures Using Fractal Geometry**	54
10-1	General	54
10-2	Definitions Relative to Fractal Based Analyses of Surfaces	54
10-3	Reporting the Results of Fractal Analyses	56
10-4	References	59
Section 11	**Specifications and Procedures for Precision Reference Specimens**	61
11-1	Scope	61
11-2	References	61
11-3	Definitions	61
11-4	Reference Specimens: Profile Shape and Application	61
11-5	Physical Requirements	62
11-6	Assigned Value Calculation	62
11-7	Mechanical Requirements	62
11-8	Marking	67
11-9	Calibration Interval	67
Section 12	**Specifications and Procedures for Roughness Comparison Specimens**	68
12-1	Scope	68
12-2	References	68
12-3	Definitions	68
12-4	Roughness Comparison Specimens	68
12-5	Surface Characteristics	68
12-6	Nominal Roughness Grades	68
12-7	Specimen Size, Form, and Lay	68
12-8	Calibration of Comparison Specimens	69
12-9	Marking	69

Figures

1-1	Schematic Diagram of Surface Characteristics	2
1-2	Measured Versus Nominal Profile	3
1-3	Stylus Profile Displayed With Two Different Aspect Ratios	4
1-4	Examples of Nominal Profiles	4
1-5	Filtering a Surface Profile	5
1-6	Profile Peak and Valley	5
1-7	Surface Profile Measurement Lengths	6

1-8 Illustration for the Calculation of Roughness Average *Ra* 7
1-9 *Rt*, *Rp*, and *Rv* Parameters 8
1-10 Surface Profile Containing Two Sampling Lengths, l_1 and l_2, Also Showing the Rp_i and Rt_i Parameters 8
1-11 The *Rt* and *R*max Parameters 9
1-12 The Waviness Height, *Wt* 9
1-13 The Mean Spacing of Profile Irregularities, *RSm* 10
1-14 The Peak Count Level, Used for Calculating Peak Density 10
1-15 Amplitude Density Function—*ADF(z)* or *p(z)* 11
1-16 The Profile Bearing Length 11
1-17 The Bearing Area Curve and Related Parameters 12
1-18 Three Surface Profiles With Different Skewness 12
1-19 Three Surface Profiles With Different Kurtosis 13
1-20 Topographic Map Obtained by an Area Profiling Method 14
1-21 Area Peaks (Left) and Area Valleys (Right) 14
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 16
1-23 Indication of Surface Lay 18
2-1 Classification of Common Instruments for Measurement of Surface Texture 20
3-1 Profile Coordinate System 23
3-2 Conical Stylus Tip 23
3-3 Other Stylus Tip Geometries 24
3-4 Aliasing 26
4-1 Schematic Diagrams of a Typical Stylus Probe and Fringe-Field Capacitance Probe 30
4-2 Effects of Various Cutoff Values 31
4-3 Examples of Profile Distortion Due to Skid Motion 33
4-4 Examples of Profile Distortion 33
7-1 The Radius of Curvature for a Surface Sine Wave 37
7-2 Stylus Tip Touching Bottom and Shoulders of Groove 38
7-3 The Stylus Tip Contact Distance, *x* 38
8-1 A Typical Phase Measuring Interferometer System 42
8-2 Demonstration of the Detector Array With Element Spacing Δ and the Measurement of the Longest Spatial Wavelength, *λL* Covering the Total Number (*N*) Pixels 42
8-3 Demonstration of the Detector Array With Element Spacing Δ and the Measurement of the Smallest Spatial Wavelength, *λR* Covering Five Pixels 43
9-1 Wavelength Transmission Characteristics for the 2RC Filter System 46
9-2 Gaussian Transmission Characteristics Together With the Uncertain Nominal Transmission Characteristic of a 2 μm Stylus Radius 47
9-3 Weighting Function of the Gaussian Profile Filter 47
9-4 Gaussian Transmission Characteristic for the Waviness Short-Wavelength Cutoff (*λsw*) or for Deriving the Roughness Mean Line Having Cutoff Wavelengths (*λc*) of 0.08 mm, 0.25 mm, 0.8 mm, 2.5 mm, and 8.0 mm 50
9-5 Gaussian Transmission Characteristic for the Roughness Long-Wavelength Cutoff Having Cutoff Wavelengths $\lambda c = 0.08$ mm, 0.25 mm, 0.8 mm, 2.5 mm, and 8.0 mm 51
9-6 Example of a Deviation Curve of an Implemented Filter From the Ideal Gaussian Filter as a Function of Spatial Wavelength 51
10-1 Self-Similarity Illustrated on a Simulated Profile 54
10-2 An Idealized Log-Log Plot of Relative Length (of a Profile) or Relative Area (of a Surface) Versus the Scale of Observation 54

10-3	An Idealized Log-Log Plot of Relative Length or Area Versus the Scale of Observation (Length-Scale or Area-Scale Plot), Showing Multi-Fractal Characteristics and Crossover Scales	55
10-4	Three Stepping Exercises From a Length-Scale Analysis on a Simulated Profile	57
10-5	Four Tiling Exercises From an Area-Scale Analysis	57
10-6	An Area-Scale Plot Including the Results of the Tiling Series in Fig. 10-5	58
11-1	Type A1 Groove	61
11-2	Type A2 Groove	61
11-3	Allowable Waviness Height *Wt* for Roughness Calibration Specimens	62
11-4	Assessment of Calibrated Values for Type A1	63
11-5	Type B1 Grooves: Set of Four Grooves	64
11-6	Type B2 or C2 Specimens With Multiple Grooves	64
11-7	Use of Type B3 Specimen	65
11-8	Type C1 Grooves	65
11-9	Type C3 Grooves	66
11-10	Type C4 Grooves	66
11-11	Unidirectional Irregular Groove Specimen Having Profile Repetition at $5\lambda c$ Intervals (Type D1 With $\lambda c = 0.8$ mm)	67

Tables

3-1	Cutoff Values for Periodic Profiles Using *RSm*	27
3-2	Cutoff Values for Nonperiodic Profiles Using *Ra*	28
4-1	Measurement Cutoffs and Traversing Lengths for Continuously Averaging Instruments Using Analog Meter Readouts	30
4-2	Measurement Cutoffs and Minimum Evaluation Lengths for Instruments Measuring Integrated Roughness Values Over a Fixed Evaluation Length	30
9-1	Limits for the Transmission Characteristics for 2RC Long-Wavelength Cutoff Filters	49
9-2	Typical Cutoffs for Gaussian Filters and Associated Cutoff Ratios	52
9-3	Typical Values for the Waviness Long-Wavelength Cutoff (λcw) and Recommended Minimum Values for the Waviness Traversing Length	52
10-1	Example of a Report on Fractal Analysis	58
11-1	Nominal Values of Depth or Height and Examples of Width for Type A1	62
11-2	Nominal Values of Depth and Radius for Type A2	63
11-3	Tolerances and Uncertainties for Types A1 and A2	63
11-4	Tip Size Estimation From the Profile Graph for Type B1	64
11-5	Typical *Ra* and *RSm* Values for Type C1	65
11-6	Tolerances and Uncertainties for Types C1 Through C4	65
11-7	Typical Values of *Ra* and *RSm* for Type C2	66
11-8	Typical Values of *Ra* for Type C4	66
11-9	Tolerances and Uncertainties for Types D1 and D2	67
12-1	Nominal Roughness Grades (*Ra*) for Roughness Comparison Specimens	68
12-2	Form and Lay of Roughness Comparison Specimens Representing Various Types of Machined Surfaces	69
12-3	Examples of Sampling Lengths for Calibration of Comparison Specimens, mm	70

Nonmandatory Appendices

A	General Notes on Use and Interpretation of Data Produced by Stylus Instruments	71
B	Control and Production of Surface Texture	73
C	A Review of Additional Surface Measurement Methods	76
D	Additional Parameters for Surface Characterization	83
E	Characteristics of Certain Area Profiling Methods	86

F	Descriptions of Area Averaging Methods	93
G	Observations on the Filtering of Surface Profiles	96
H	Reference Subroutines	97
I	A Comparison of ASME and ISO Surface Texture Parameters	105
J	Functional Standards	107

FOREWORD

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
Revision — June 1995
Revision — October 2002

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 as follows:

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

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

Technical drawings referring to a specific version of the ASME B46.1 Standard (e.g., ASME B46.1-2009) refers to the rules and definitions given in that version of the surface texture standard as indicated. For technical drawings that do not indicate a specific ASME B46.1 surface texture standard, the rules and definitions given in the ASME B46.1 revision in effect at the release date of the drawing must be used.

The ASME B46 Committee contributes to international standardization activities related to surface texture measurement and analysis as referenced in ISO/TR 14368:1995, Geometrical Product Specification (GPS) — Masterplan.

The present Standard includes 12 sections as follows:

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, *Ra*. These include rms roughness *Rq*, waviness height *Wt*, the mean spacing of profile irregularities *RSm*, 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 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 *Ra*.

Section 5, Measurement Techniques for Area Profiling, 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, *Sa* and *Sq*, as alternatives to the traditional profiling parameters.

Section 6, Measurement Techniques for Area Averaging, discusses 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.

Section 7, Nanometer Surface Texture and Step Height Measurements by Stylus Profiling Instruments, addresses the use of contacting profilometry in the measurement of surface texture features whose height dimensions are typically measured within the scale of nanometers. Section 7 may be applicable to such industries as the semiconductor, data storage, and micro electromechanical systems (MEMS) manufacturers.

Section 8, Nanometer Surface Roughness as Measured With Phase Measuring Interferometric Microscopy, addresses the use of optical noncontact techniques for measuring highly polished surfaces. Section 8 may be applied to the measurement of such items as polished silicon wafers, optical components and precision mechanical components.

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, Terminology and Procedures for Evaluation of Surface Textures Using Fractal Geometry, introduces the field of fractal analysis as applied to measuring surface texture. Introductions of various techniques and terms are included to allow for lateral scale specific interpretation of surface texture.

Section 11, Specifications and Procedures for Precision Reference Specimens, describes different types of specimens useful in the calibration and testing of surface profiling instruments. It is based on ISO 5436, Part 1, Material Measures, and 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.

ASME B46.1-2009 was approved by the American National Standards Institute on October 22, 2009.

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Classification and Designation of Surface Qualities

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Proposing Revisions. Revisions are made periodically to the Standard to incorporate changes that appear necessary or desirable, as demonstrated by the experience gained from the application of the Standard. Approved revisions will be published periodically.

The Committee welcomes proposals for revisions to this Standard. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

Proposing a Case. Cases may be issued for the purpose of providing alternative rules when justified, to permit early implementation of an approved revision when the need is urgent, or to provide rules not covered by existing provisions. Cases are effective immediately upon ASME approval and shall be posted on the ASME Committee Web page.

Requests for Cases shall provide a Statement of Need and Background Information. The request should identify the Standard, the paragraph, figure or table number(s), and be written as a Question and Reply in the same format as existing Cases. Requests for Cases should also indicate the applicable edition(s) of the Standard to which the proposed Case applies.

Interpretations. Upon request, the B46 Committee will render an interpretation of any requirement of the Standard. Interpretations can only be rendered in response to a written request sent to the Secretary of the B46 Standards Committee.

The request for interpretation should be clear and unambiguous. It is further recommended that the inquirer submit his/her request in the following format:

Subject:	Cite the applicable paragraph number(s) and the topic of the inquiry.
Edition:	Cite the applicable edition of the Standard for which the interpretation is being requested.
Question:	Phrase the question as a request for an interpretation of a specific requirement suitable for general understanding and use, not as a request for an approval of a proprietary design or situation. The inquirer may also include any plans or drawings, which are necessary to explain the question; however, they should not contain proprietary names or information.

Requests that are not in this format may be rewritten in the appropriate format by the Committee prior to being answered, which may inadvertently change the intent of the original request.

ASME procedures provide for reconsideration of any interpretation when or if additional information that might affect an interpretation is available. Further, persons aggrieved by an interpretation may appeal to the cognizant ASME Committee or Subcommittee. ASME does not "approve," "certify," "rate," or "endorse" any item, construction, proprietary device, or activity.

Attending Committee Meetings. The B46 Standards Committee regularly holds meetings which are open to the public. Persons wishing to attend any meeting should contact the Secretary of the B46 Standards Committee.

EXECUTIVE SUMMARY

1 GENERAL

In cases of disagreement regarding the interpretation of surface texture measurements, it is recommended that measurements with skidless stylus based instruments with Gaussian filtering be used as the basis for interpretation. The following key measurement parameters must be established for proper surface texture specification and measurement.

2 FILTERING

The spatial wavelengths to be included in a surface texture measurement are generally limited by digital bandpass filtering. For measurement of roughness, short wavelength cutoff, λs, specifies the short spatial wavelength limit and is defined as the wavelength where the Gaussian filter will attenuate the true profile by 50%. Spatial wavelengths less than λs are severely attenuated and minimally contribute to the roughness measurement.

The roughness long wavelength cutoff, λc, specifies the long spatial wavelength limit and is defined as the wavelength where the Gaussian filter will attenuate the true profile by 50%. Spatial wavelengths greater than λc are severely attenuated and minimally contribute to the roughness measurement.

The ratio of λc to λs (λc:λs) is the bandwidth of the measurement. Some instruments allow the selection of λc and λs individually and/or the selection of a bandwidth, typically 100:1 or 300:1. The spatial wavelengths comprising the texture between λs and λc are minimally attenuated by the Gaussian filter.

The cutoffs, λc and λs, should be chosen by the designer in light of the intended function of the surface. When choosing λc and λs, one must be cognizant that the surface features not measured within the roughness cutoff bandwidth may be quite large and may affect the intended function of the surface. Thus in some cases it may be necessary to specify both surface roughness and waviness.

When surface waviness control is important, digital bandpass filtering is applied similarly as it is for roughness filtering. For waviness, the waviness short wavelength cutoff (λsw) and waviness long wavelength cutoff (λcw) are applied to obtain the waviness profile. An important consideration is the correspondence of the roughness long wavelength cutoff and the waviness short wavelength cutoff. When these respective cutoff values are not equal, the discrimination of the roughness and waviness features of a given surface can become confounded.

On all surface texture specifications as of January 1997, λc and λs must be stated. When λc and λs are not specified, guidelines are given in paras. 3-3.20.1 and 3-3.20.2 of ASME B46.1-2009 for the metrologist to establish λc and λs. These guidelines are intended to include the dominant features of the surface in the measurement whether these surface features are relevant to the function of the surface or not.

3 STYLUS TIP RADIUS

The stylus tip radius may be chosen by the designer or metrologist based on the value of λs (i.e., the short wave cutoff). For λs equal to 2.5 μm, the tip radius should typically be 2 μm or less. For λs equal to 8 μm, the tip radius should typically be 5 μm or less. For λs equal to 25 μm, the tip radius should typically be 10 μm or less.

4 STYLUS FORCE

The maximum static measuring force is determined by the radius of the stylus and is chosen to assure minimal damage to the surface and that constant contact is maintained with the surface. Specific recommendations for stylus force may be found in para. 3-3.5.2 of the ASME B46.1-2009 standard.

5 MEASUREMENT PARAMETERS

Many surface finish height parameters are in use throughout the world. From the simplest specification of a single roughness parameter to multiple roughness and waviness parameter specifications of a given surface, product designers have many options for specifying surface texture in order to control surface function. Between these extremes, designers should consider the need to control roughness height (e.g., *Ra* or *Rz*), roughness height consistency (e.g., *R*max), and waviness height (e.g., *Wt*). Waviness is a secondary longer wavelength feature that is only of concern for particular surface functions and finishing processes. A complete description of the various texture parameters may be found in Section 1 of the B46.1-2009 standard.

6 SURFACE TEXTURE SYMBOLS

Once the various key measurement parameters are established, ISO 1302:2002, may be used to establish the proper indication on the relevant engineering drawings.

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.

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] Le Système International d'Unités.

1-1.4 References. Unless otherwise specified on the engineering drawing or other relevant documents, this Standard is to be used in conjunction with ISO 1302:2002, (GPS) — Indication of Surface Texture in Technical Product Documentation, that prescribes engineering drawing and other related documentation practices for specifying surface texture. Relevant standards that may be used in design and measurement are the following:

ASME B89.6.2-1973 (R2003), Temperature and Humidity Environment for Dimensional Measurement

ASME Y14.5M-1994 (R2004), Dimensioning and Tolerancing, Engineering Drawings and Related Documentation Practices

Publisher: The American Society of Mechanical Engineers (ASME), Three Park Avenue, New York, NY 10016; Order Department: 22 Law Drive, Box 2300, Fairfield, NJ 07007-2300 (www.asme.org)

ISO 1302:2002, Geometrical Product Specifications (GPS) — Indication of surface texture in technical product documentation

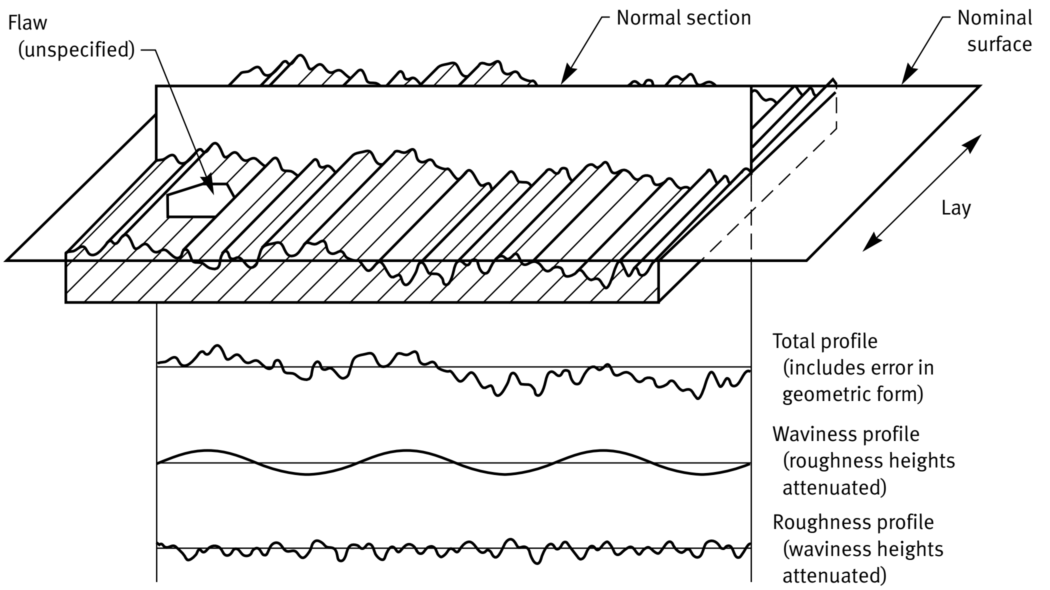
Publisher: International Organization for Standardization (ISO), 1 ch. de la Voie-Creuse, Case Postale 56, CH-1211, Genève 20, Switzerland/Suisse (www.iso.org)

ASME B46.1, Table J-1 of Nonmandatory Appendix J is a partial list of specific industry standards that reference surface texture specifications. Users are encouraged to submit additional industry standards to be considered as references in future versions of ASME B46.1, Nonmandatory Appendix J.

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.

Fig. 1-1 Schematic Diagram of Surface Characteristics



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.

1-2.2 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.

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

roughness: the finer spaced 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. B-1 of Nonmandatory 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 (see para. 1-6.5 and Fig. 1-23).

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.

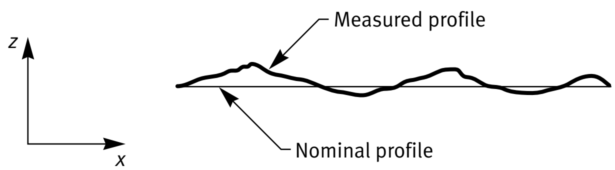
flaws: unintentional, unexpected, and unwanted interruptions in the topography typical of a surface. Topography is defined in para. 1-5.1. However, these topographical interruptions are considered to be flaws only when agreed upon in advance by buyer and seller. If flaws are specified, the surface should 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.

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

[2] ASME/ANSI B89.3.1-1972 (R1997), *Measurement of Out-of-Roundness.*

Fig. 1-2 Measured Versus Nominal Profile



three-dimensional (area) or two-dimensional (profile) methods.

1-3.1 Profiles

profile: the curve of intersection of a normal sectioning plane with the surface (see Fig. 1-1).

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

nominal profile: a profile of the nominal surface: a straight line or smooth curve (see Fig. 1-4).

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 representation of the measured profile for which various 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.

form-suppressed profile: a modified profile obtained by various techniques to attenuate dominant form such as curvature, tilt, etc. An example of a mechanical technique involves the use of a skidded instrument (see Section 4).

primary profile: a modified profile after the application of the short wavelength filter, λs (see Section 9).

NOTE: This corresponds to *P* (profile) parameters per ISO 4287-1997.

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.

1-3.1.1 Aspect Ratio. In displays of surface profiles generated by instruments, heights are usually magnified many times more than distances along the 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 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 measuring 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 the unfiltered profile and the waviness profile 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.

height (z) range: the largest overall peak-to-valley surface height that can be accurately detected by a measuring instrument. This is a key specification for a measuring instrument.

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 root mean square (rms) roughness of a surface whose actual

[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

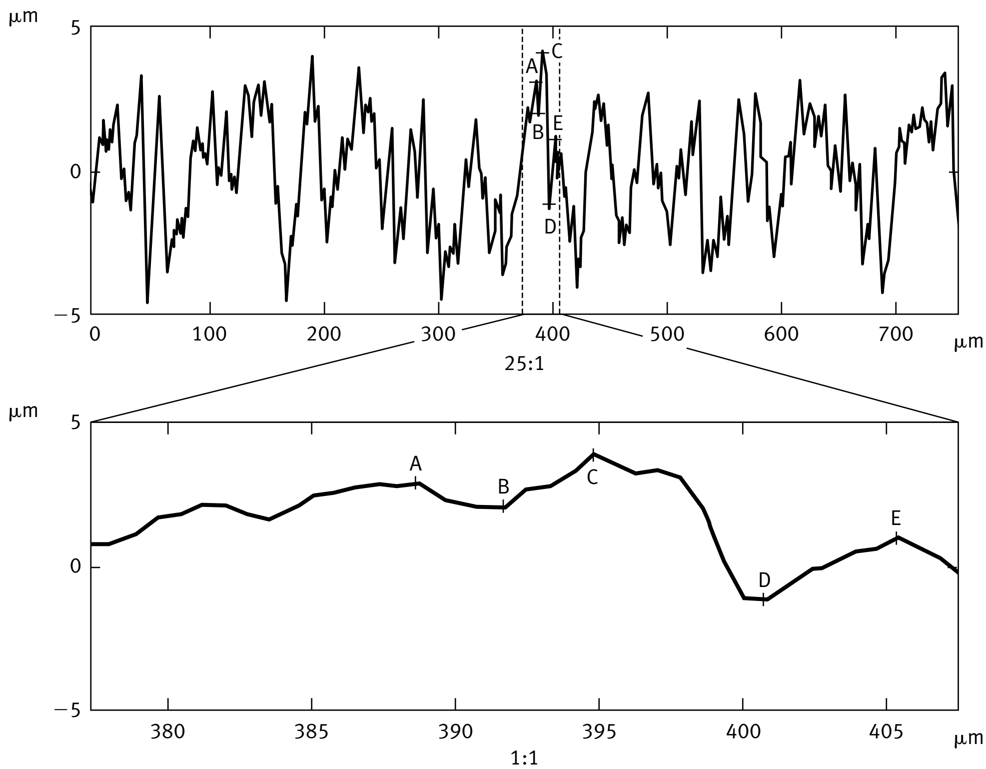


Fig. 1-4 Examples of Nominal Profiles

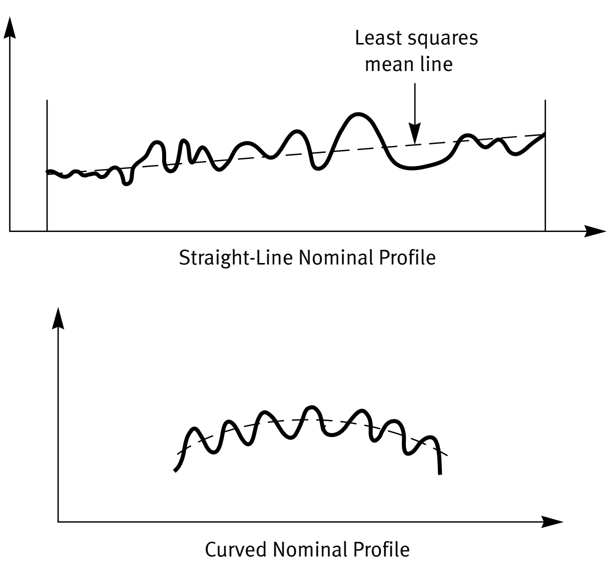
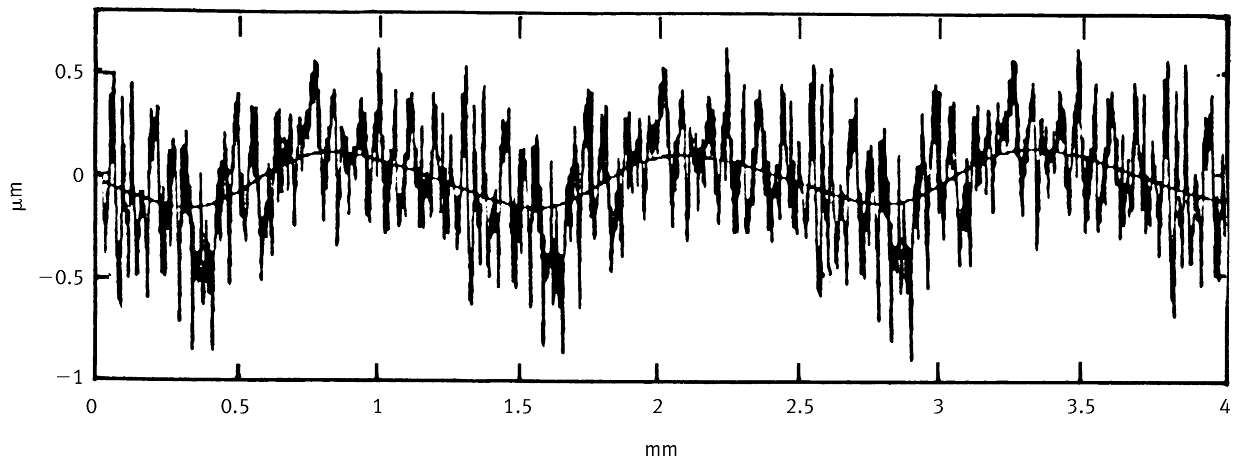
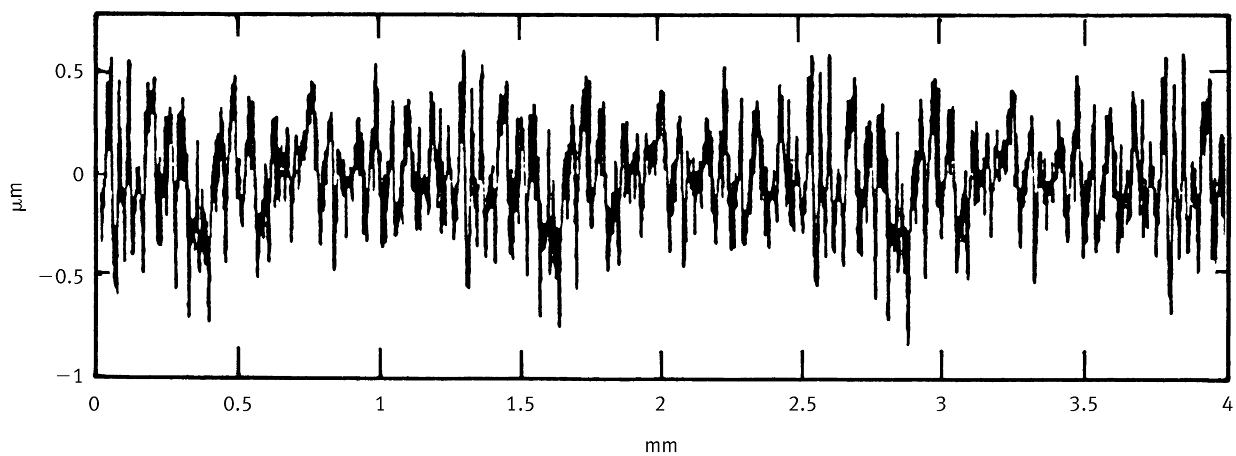


Fig. 1-5 Filtering a Surface Profile



(a) Unfiltered Profile and Filtered Mean Line



(b) Roughness Profile

Fig. 1-6 Profile Peak and Valley

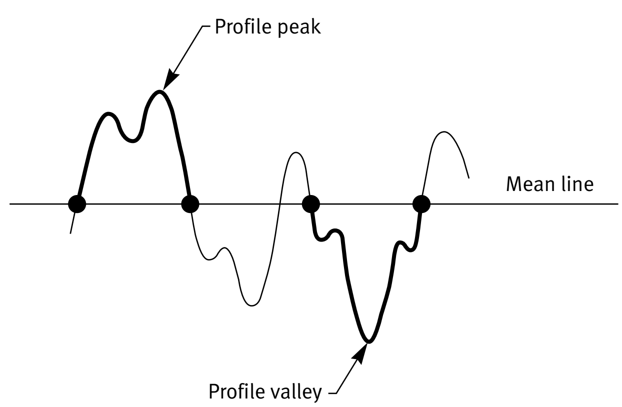
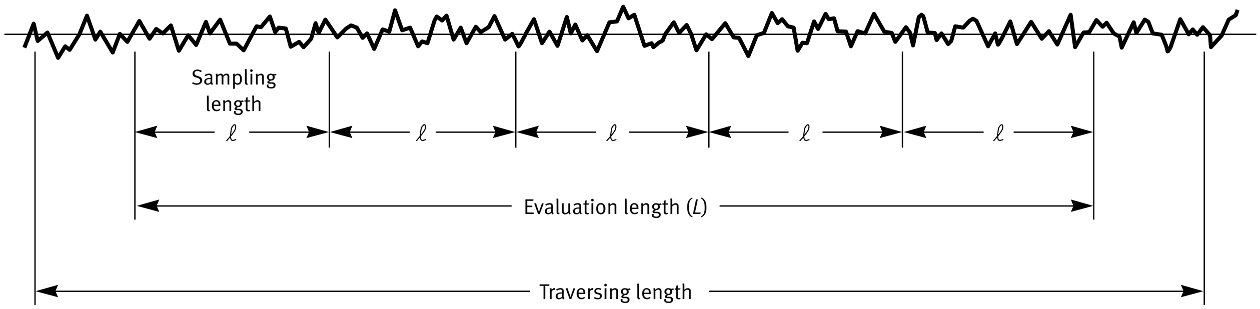


Fig. 1-7 Surface Profile Measurement Lengths



roughness is significantly smaller than the system background noise.

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 para. 1-3.5).

spatial wavelength, λ: the lateral 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,[5] 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 Measurement and Analysis Lengths

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).

evaluation length (L): length in the direction of the X-axis used for assessing the profile under evaluation. The evaluation length for roughness is termed *Lr* and the evaluation length for waviness is termed *Lw*.

sampling length (l): length in the direction of the X-axis used for identifying the widest irregularities that are of interest for the profile under evaluation. The sampling length is always less than or equal to the evaluation length. The sampling length for roughness is termed *lr* and the sampling length for waviness is termed *lw*.

roughness sampling length,[6] *lr:* 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,[7] *λc:* 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). 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., $lr = \lambda c$). The range of selectable roughness long-wavelength cutoffs is a key specification for a surface measuring instrument.

roughness short-wavelength cutoff, λs: the spatial wavelength shorter than which the fine asperities for the surface roughness profile are attenuated. The nominal values of this parameter are expressed in micrometers (μm). 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.

waviness sampling length,[7] *lw:* the sampling length specified to separate the profile irregularities designated as

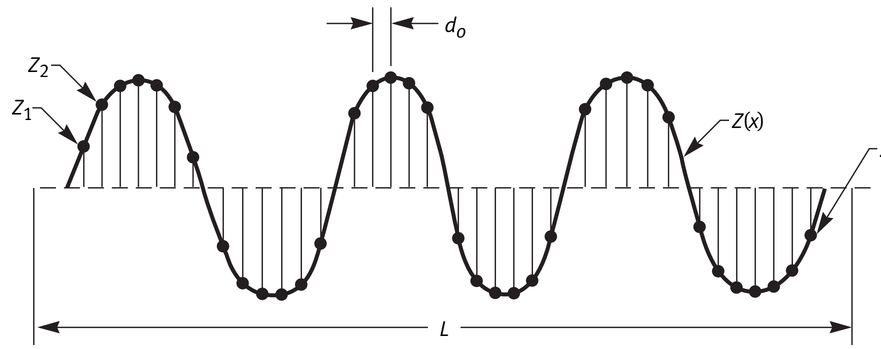
[4] J. M. Bennett and L. Mattsson, *Introduction to Surface Roughness and Scattering* (Washington, DC: Optical Society of America, 1989), 22.

[5] "Interpolation With Splines and FFT in Wave Signals," Sanchez Fernandez, L. P., *Research in Computing Science*, Vol. 10 (2004):387–400.

[6] See also Sections 4 and 9 and Nonmandatory Appendix A.

[7] 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. 1-8 Illustration for the Calculation of Roughness Average *Ra*



Ra = average deviation of roughness profile $Z(x)$ from the mean line
= total shaded area/L

waviness from those irregularities designated as form. The waviness sampling length may be determined by electrical analog filtering, digital filtering, or geometrical truncation of the profile into the appropriate lengths.

waviness long-wavelength cutoff, λcw: the spatial wavelength longer than which the widely spaced undulations of the surface profile are attenuated to separate form from waviness. When an electrical or digital filter is used, the waviness long-wavelength cutoff value determines and is equal to the waviness sampling length (i.e., $lw = \lambda cw$). The range of selectable waviness long-wavelength cutoffs is a key specification for a surface measuring instrument.

waviness short-wavelength cutoff, λsw: the spatial wavelength shorter than which the roughness profile fluctuations of the surface profile are attenuated by electrical or digital filters. This rating is generally set equal in value to the corresponding roughness long-wavelength cutoff ($\lambda sw = \lambda c$).

Typical values for the various measurement and analysis lengths are discussed in Sections 3 and 9.

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.

Nonmandatory Appendix H provides example computer subroutines for the calculation of several of these parameters.

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 (μm).[8]

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,[9] *Ra:* 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, Ra 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 centerline.

Analytically, Ra is given by the following equation:

$$Ra = (1/L)\int_o^L |Z(x)|dx$$

For digital instruments an approximation of the Ra 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.

$$Ra = (|Z_1| + |Z_2| + |Z_3| \dots |Z_N|) / N$$

---

[8] 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 μm, and microinch may be abbreviated as μin. One microinch equals 0.0254 μm (μin. = 0.0254 μm). The nanometer (nm) and the angstrom unit (Å) are also used in some industries. 1 nm = 0.001 μm, 1Å = 0.1 nm.

[9] Roughness average is also known as centerline arithmetic average (AA) and centerline average (CLA).

Fig. 1-9 *Rt*, *Rp*, and *Rv* Parameters

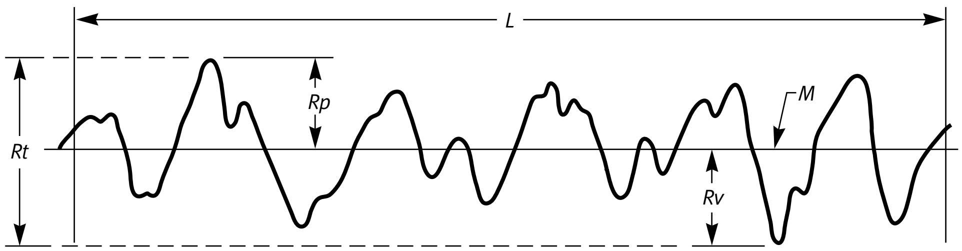
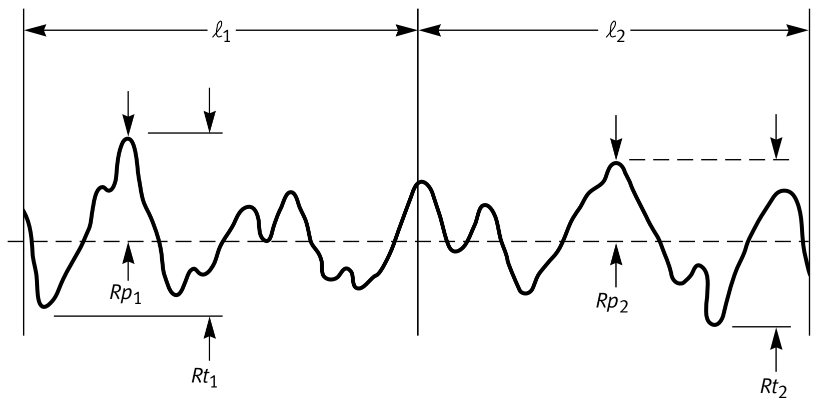


Fig. 1-10 Surface Profile Containing Two Sampling Lengths, l_1 and l_2, Also Showing the Rp_i and Rt_i Parameters



root mean square (rms) roughness, Rq: the root mean square average of the profile height deviations taken within the evaluation length and measured from the mean line. Analytically, it is given by the following equation:

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

The digital approximation is as follows:

$$Rq = [(Z^2{}_1 + Z^2{}_2 + Z^2{}_3 + \ldots Z^2{}_N)/N]^{1/2}$$

maximum profile peak height, Rp: the distance between the highest point of the profile and the mean line within the evaluation length (see Fig. 1-9).

Rp_i: the distance between the highest point of the profile and the mean line within a sampling length segment labeled *i* (see Fig. 1-10).

average maximum profile peak height, Rpm: the average of the successive values of Rp_i calculated over the evaluation length.

maximum profile valley depth, Rv: 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, Rt: the vertical distance between the highest and lowest points of the profile within the evaluation length (see Fig. 1-9).

$$Rt = Rp + Rv$$

Rt_i: the vertical distance between the highest and lowest points of the profile within a sampling length segment labeled *i* (see Fig. 1-10).

average maximum height of the profile, Rz: the average of the successive values of Rt_i calculated over the evaluation length.

maximum roughness depth, Rmax: the largest of the successive values of Rt_i calculated over the evaluation length (see Fig. 1-11).

1-4.1.2 Waviness Height Parameters

waviness height, Wt: 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 *Rt* and *R*max Parameters

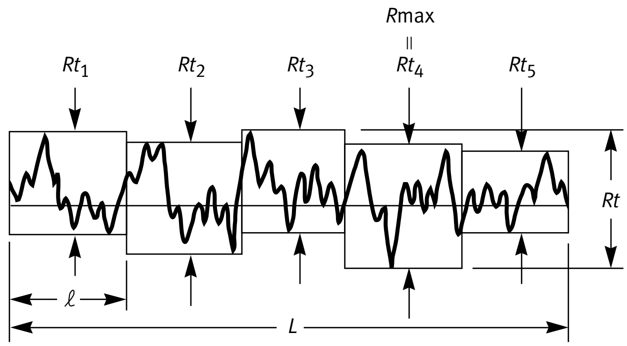
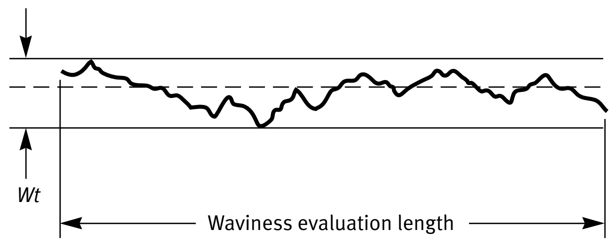


Fig. 1-12 The Waviness Height, *Wt*



1-4.2 Spacing Parameters

spacing parameter: a distance that characterizes the lateral spacings between the individual profile asperities.

mean spacing of profile irregularities, RSm: the mean value of the spacing between profile irregularities within the evaluation length. In Fig. 1-13

$$RSm = (1/n)\sum_{i=1}^{n} Sm_i$$

NOTE: The parameter *RSm* requires height and spacing discrimination. If not otherwise specified, the default height discrimination shall be 10% of *Rz* (i.e., ±5% of *Rz* from the mean line) and the default spacing discrimination shall be 1% of the sampling length; both conditions shall be met.

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] *Pc:* the number of SAE peaks per unit length measured at a specified peak count level over the evaluation length.

[10] SAE J911 — March 1998 (Society of Automotive Engineers).

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 over the evaluation length (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 the following:

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

(b) as a height from the mean line

(c) as a percentage of the *Rt* value relative to the highest peak (see Fig. 1-16)

profile bearing length ratio, tp: the ratio of the profile bearing length to the evaluation length at a specified level *p*. The quantity *tp* should be expressed in percent.

$$tp = \frac{b_1 + b_2 + b_3 + \ldots + b_n}{L} \times 100\%$$

bearing area curve, BAC: (also called the Abbott-Firestone curve) is related to the cumulative distribution of the ADF. It shows how the profile bearing length ratio varies with level.

Fig. 1-13 The Mean Spacing of Profile Irregularities, *RSm*

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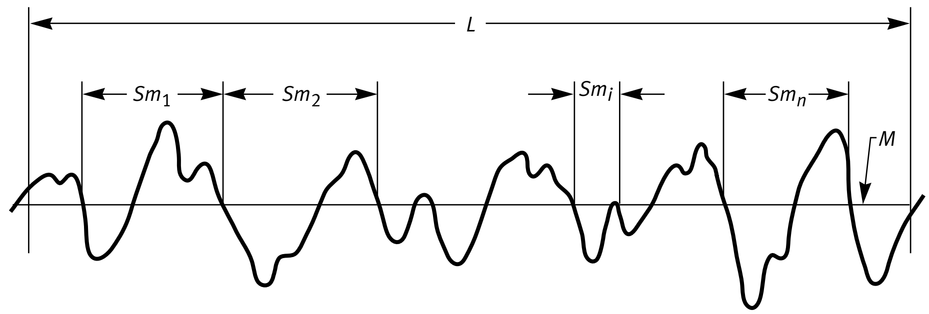
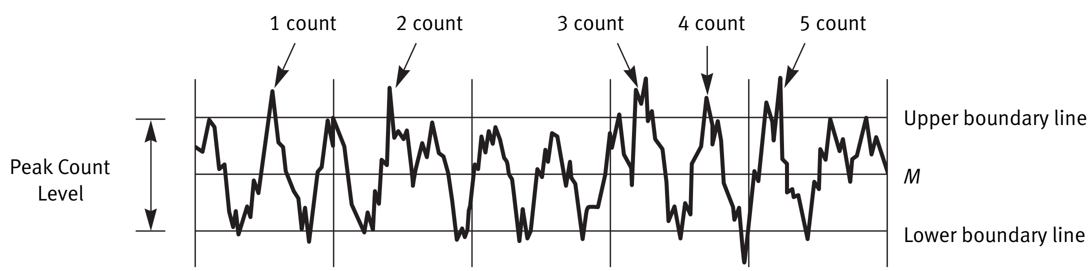


Fig. 1-14 The Peak Count Level, Used for Calculating Peak Density



Htp: difference in the heights for two profile bearing length ratios *tp* set at selectable values (see Fig. 1-17).

skewness, Rsk: a measure of the asymmetry of the profile about the mean line calculated over the evaluation length (see Fig. 1-18). In analytic form as follows:

$$Rsk = \frac{1}{Rq^3}\frac{1}{L}\int_o^L Z^3(x)dx$$

For a digitized profile, a useful formula is as follows:

$$Rsk = \frac{1}{Rq^3}\frac{1}{N}\sum_{j=1}^{N} Z_j^3$$

kurtosis, Rku: a measure of the peakedness of the profile about the mean line calculated over the evaluation length (see Fig. 1-19). In analytic form as follows:

$$Rku = \frac{1}{Rq^4}\frac{1}{L}\int_o^L Z^4(x)dx$$

For a digitized profile, a useful formula is as follows:

$$Rku = \frac{1}{Rq^4}\frac{1}{N}\sum_{j=1}^{N} Z_j^4$$

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 the following equation:[11]

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

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 with evaluation length *L*, consisting of *N* equidistant points separated by a sampling interval d_o, the function may be approximated by the following equation:

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

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

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

Fig. 1-15 Amplitude Density Function — *ADF(z)* or *p(z)*

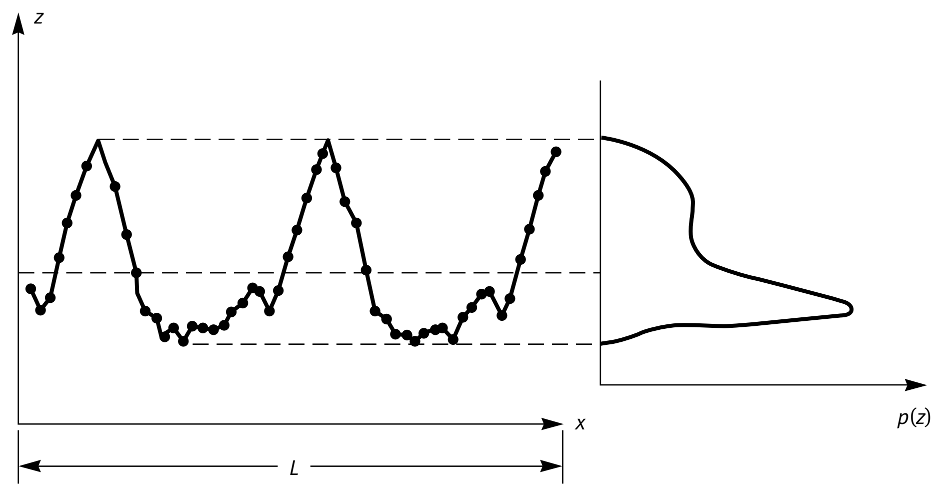


Fig. 1-16 The Profile Bearing Length

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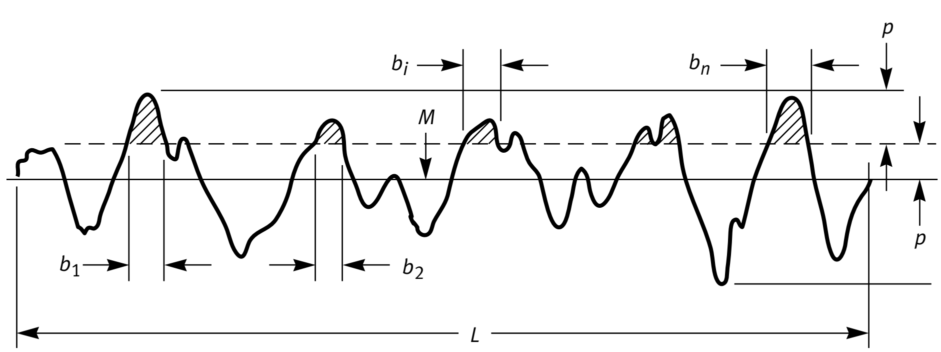
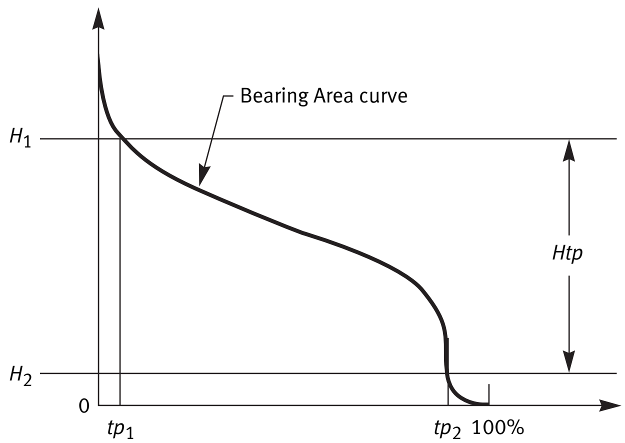
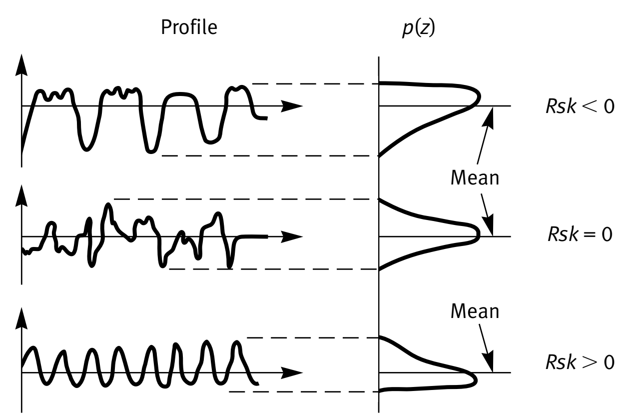


Fig. 1-17 The Bearing Area Curve and Related Parameters



tp_1, tp_2 = selected profile bearing length ratios
H_1, H_2 = levels for tp_1 and tp_2
Htp = height between bearing ratios

Fig. 1-18 Three Surface Profiles With Different Skewness



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

may also be calculated by taking the Fourier transform of the autocovariance function discussed next.

autocovariance function, ACV(τ): the ACV(τ) is given by an overlap integral of shifted and unshifted profiles over the evaluation length and is also equal to the inverse Fourier transform of the *PSD*. The ACV(τ) is given by the following equation:

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

where τ is the shift distance. For a finite, digitized profile, it may be approximated by the following equation:

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

where $\tau = j' d_o$

autocorrelation function, ACF(τ): The normalized autocovariance function is as follows:[11]

$$\text{ACF}(\tau) = \text{ACV}(\tau)/Rq^2$$

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, RΔa: 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 the following equation:

$$R\Delta a = (1/L) \int_o^L |dZ|dx|dx$$

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

$$R\Delta a = \frac{1}{N} \sum_{i=1}^{N} |\Delta_i|$$

where[12]

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

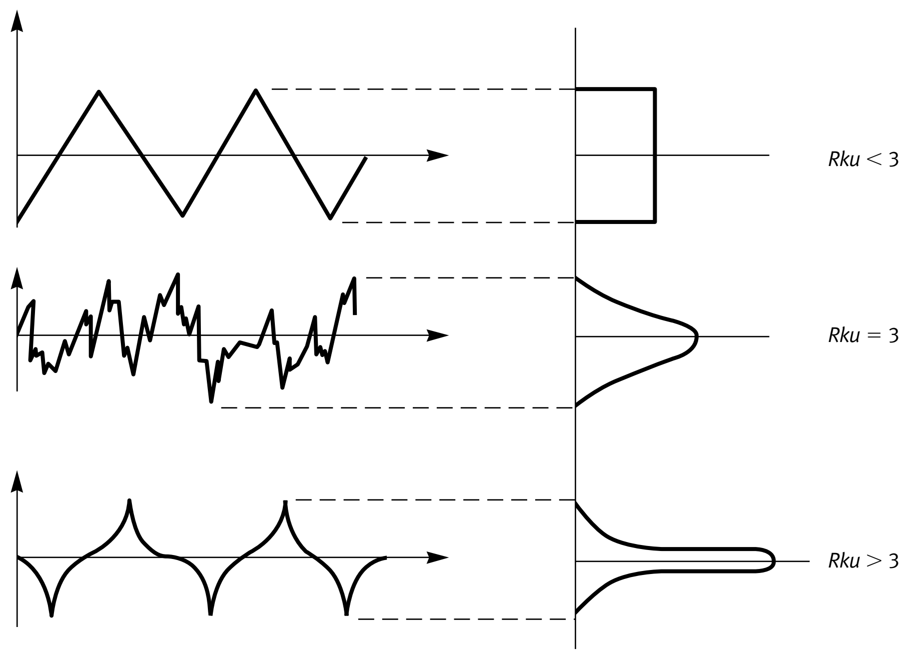
The selected value of d_o influences the value of $R\Delta a$.

root mean square slope, RΔq: 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 the following equation:

$$R\Delta q = \left(1/L \int_o^L (dZ/dx)^2\, dx\right)^{1/2}$$

[12] D.G. Chetwynd, Slope Measurement in Surface Texture Analysis, *Journal of Mechanical Engineering, Sci.* 20, 115 (1978).

Fig. 1-19 Three Surface Profiles With Different Kurtosis



Digitally, it may be given by the following equation:

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

where Δ_i is given above. Just as for the average slope $R\Delta a$ the selected value of d_o influences the value of $R\Delta q$.

1-4.5 Linear Material Ratio Curve Height Parameters. Related to the profile bearing length is the linear material ratio curve, also known as the bearing area curve. Parameters Rpk, Rk, Rvk, Mr1, and Mr2 derived from the linear material ratio curve, may be found in the normative reference, ISO 13565-2:1996 which, through being referenced in this text, constitutes a provision of this National Standard.

1-4.6 Material Probability Curve Height Parameters. Related to the profile bearing length is the material probability curve. Parameters Rpq, Rvq, and Rmq, derived from the material probability curve, may be found in the normative reference, ISO 13565-3:1996 which, through being referenced in this text, constitutes a provision of this National Standard.

1-5 Definitions Related to the Measurement of Surface Texture by Area Profiling and Area Averaging Methods

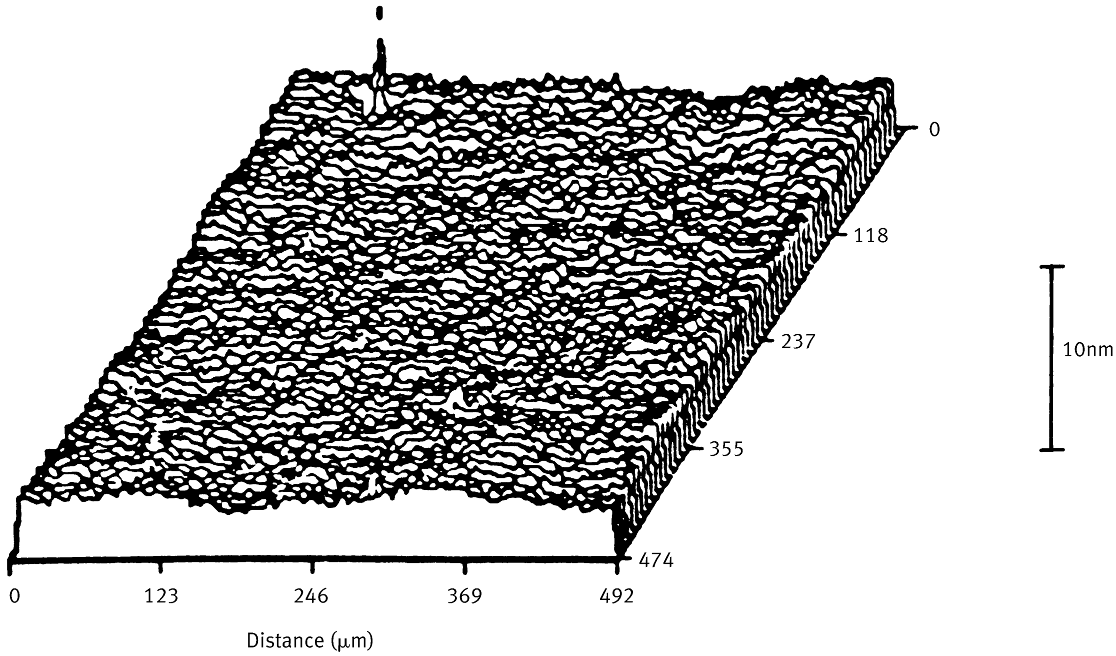
1-5.1 General. Several types of surface measurement techniques are used to quantify the surface texture over a selected area of a surface instead of over single profiles. Area methods may be divided into two classes, area profiling methods and area averaging methods, as defined below.

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).

Fig. 1-20 Topographic Map Obtained by an Area Profiling Method



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.

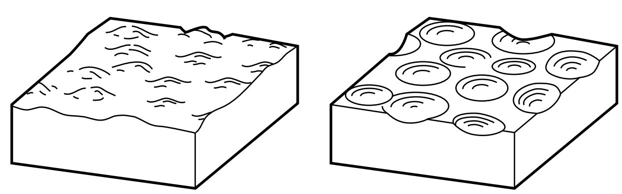
1-5.2 Reference Mean Surfaces

mean surface: the three-dimensional reference surface about which the topographic deviations are 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.

Fig. 1-21 Area Peaks (Left) and Area Valleys (Right)



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, As: 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, Ae: the total area over which the values of surface parameters are evaluated. For proper statistics, it may contain a number of sampling areas. $Ae = L_x L_y$ 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, Sa: the arithmetic average of the absolute values of the measured height deviations from the mean surface taken within the evaluation area. Analytically, *Sa* is given in Cartesian coordinates by the following equation:

$$Sa = (1/Ae) \int_o^{Ly} \int_o^{Lx} |Z(x,y)| \, dxdy$$

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

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

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

$$Sq = \left((1/Ae \int_0^{Ly} \int_0^{Lx} Z^2(x,y) \, dxdy \right)^{1/2}$$

The digital approximation is as follows:

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

maximum area peak height, Sp: the maximum height in the evaluation area with respect to the mean surface.

maximum area valley depth, Sv.: the absolute value of the minimum height in the evaluation area with respect to the mean surface.

area peak-to-valley height, St: the vertical distance between the maximum height and the maximum depth in the evaluation area, and is as follows:

$$St = Sp + Sv$$

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 *Sq* 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.

1-6.2 Waviness Parameters

area waviness height, SWt: 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, Ssk: a measure of the asymmetry of surface heights about the mean surface. Analytically, *Ssk* may be calculated from the following:

$$Ssk = \frac{1}{(Sq)^3 \, Ae} \int_o^{Ly} \int_o^{Lx} Z^3(x,y) dxdy$$

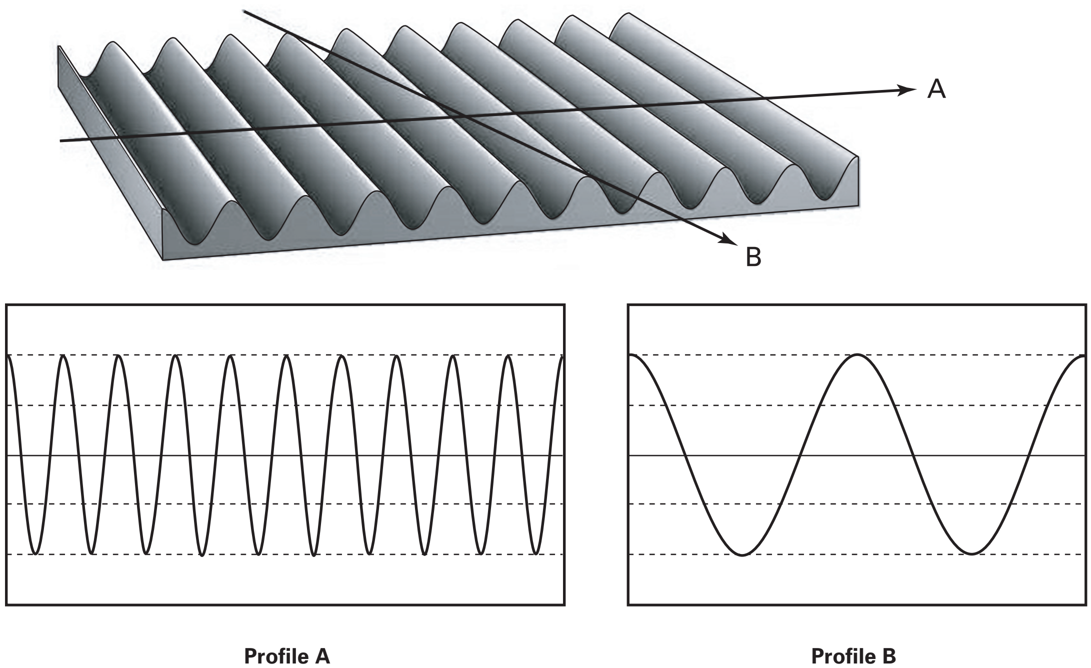
For digitized profiles it may be calculated from the following:

$$Ssk = \frac{1}{(Sq)^3} \frac{1}{MN} \sum_{k=1}^{M} \sum_{j=1}^{N} Z_{jk}^3$$

kurtosis, Sku: a measure of the peakedness of the surface heights about the mean surface. Analytically, *Sku* may be calculated from the following:

$$Sku = \frac{1}{(Sq)^4 \, Ae} \int_o^{Ly} \int_o^{Lx} Z^4(x,y) dxdy$$

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



For a digitized profile, it may be calculated from the following:

$$Sku = \frac{1}{(Sq)^4} \frac{1}{MN} \sum_{k=1}^{M} \sum_{j=1}^{N} Z_{jk}^4$$

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

1-6.5 Other Parameters

surface 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 root mean square slope, Sdq: the root mean square sum of the *x* and *y* derivatives of the measured topography over the evaluation area.

area root mean square directional slope, Sdq(θ): the root mean square average of the derivative of the measured topography along a selected direction, *θ*, calculated over the sampling 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.

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:

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

A digital approximation is given by the following:

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

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 following formula:

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

The digital approximation may be given by the following:

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

where

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

area autocorrelation function, AACF*:* the normalized area autocovariance function as indicated by the following equation:

$$\mathrm{AACF}(\tau_x, \tau_y) = \mathrm{AACV}(\tau_x, \tau_y)/(Sq)^2$$

texture aspect ratio,[13] *Str:* is a measure of the spatial isotropy or directionality of the surface texture. For a surface with a dominant lay (see Fig.1-22), the *Str* parameter will approach 0.00, whereas for a spatially isotropic texture (see Fig.1-20), *Str* will approach 1.00. The *Str* parameter is derived from the area autocovariance function, AACV, and is given by the following:

$$Str = \frac{Length-of-fastest-decay-AACV-in-any-direction}{Length-of-slowest-decay-AACV-in-any-direction}$$

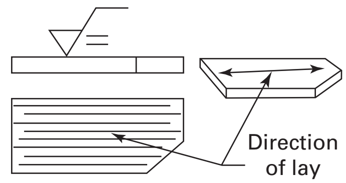
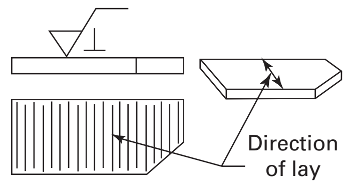
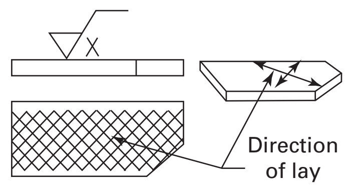
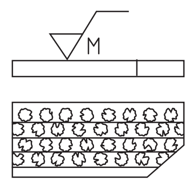
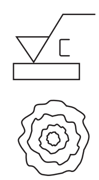
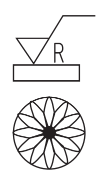
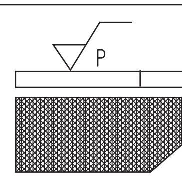
texture direction,[13] *Std:* is determined by the APSD and is a measure of the angular direction of the dominant lay comprising a surface. *Std* is defined relative to the Y-axis. Thus a surface with a lay along the Y-axis will result in a *Std* value of 0 deg. A positive *Std* value is measured clockwise from the Y-axis.

For indication of surface lay, see Fig. 1-23.

[13] K. J. Stout, *Development of Methods for the Characterisation of Roughness in Three Dimensions*, 2000, Penton Press, London, UK ISBN 1 8571 8023 2.

Fig. 1-23 Indication of Surface Lay

(This material is reproduced from ISO 1302:2002)

Graphical symbol	Interpretation and example	
=	Parallel to plane of projection of view in which symbol is used	
⊥	Perpendicular to plane of projection of view in which symbol is used	
X	Crossed in two oblique directions relative to plane of projection of view in which symbol is used	
M	Multidirectional	
C	Approximate circular relative to center of surface to which symbol applies	
R	Approximate radial relative to center of surface to which symbol applies	
P	Lay is particulate, nondirectional, or protuberant	

GENERAL NOTE: If it is necessary to specify a surface pattern which is not clearly defined by these symbols, this shall be achieved by the addition of a suitable note to the drawing.

Section 2
Classification of Instruments for Surface Texture Measurement

2-1 Scope

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 and radius, and sampling interval are to be determined using Section 9, Table 9-2, based on the desired roughness cutoff (λc). If the roughness cutoff is not specified, it may be determined as per Section 3, Table 3-1 or Table 3-2, as appropriate. The recommended maximum stylus force is given in Section 3, para. 3-3.5.2, based on the desired tip radius.

If the surface structures to be assessed require a smaller short wavelength cutoff, λs, than 2.5 μm as given in Section 9, Table 9-2, then it is recommended that either a Type I (Profiling Contact Skidless Instruments) instrument or a Type III (Scanned Probe Microscopy) instrument, applied as described in Section 7, be used as the basis for interpretation.

The above recommendations do not apply if significant damage can occur to the surface when using the Type I or Type III instrument.

2-3 Classification Scheme

2-3.1 Type I: Profiling Contact Skiddless Instruments

2-3.1.1 Properties

(a) measuring range often includes both smooth and rough surfaces

(b) measures 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

(g) results may be sensitive to material hardness and steep surface slopes

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. See Section 3 of this Standard.

2-3.2 Type II: Profiling Noncontact Instruments. These techniques generally use an optical or electronic sensor.

2-3.2.1 Properties

(a) measuring range often includes both smooth and rough surfaces

(b) measures roughness and for some types 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

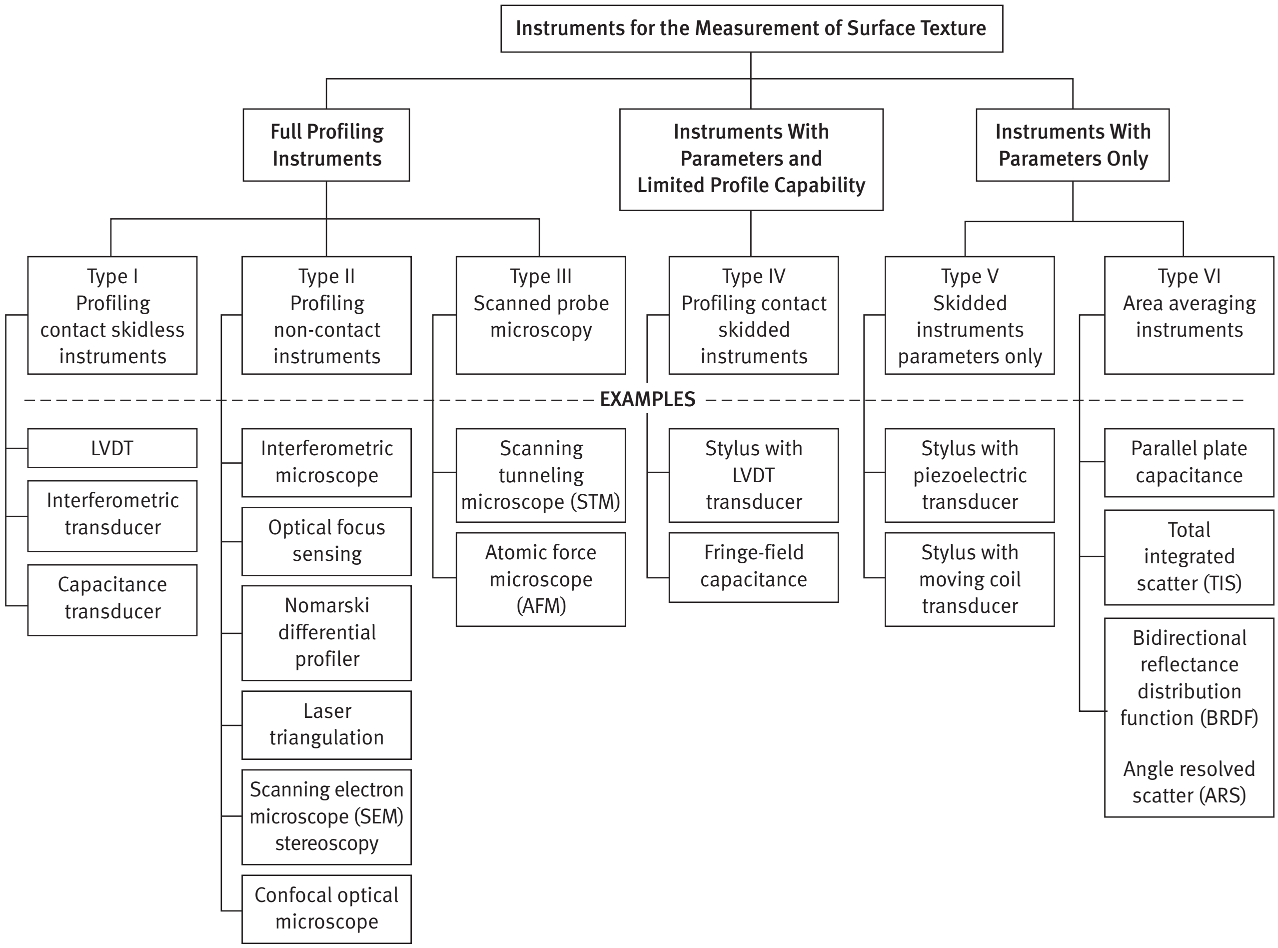
(d) for microscope based instruments, imaging objectives are often interchangeable providing surface imaging resolution to submicrometers or field of view to several millimeters

(e) can generate filtered or unfiltered profiles, yet the selection of filter types and parameters may vary with instrument techniques or defined data analysis

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

(g) depending on instrument type, results may be sensitive to the following material properties: surface reflectivity, steep surface slopes, the presence of thin-films and dissimilar materials

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 profiler
(*d*) laser triangulation
(*e*) scanning electron microscope (SEM) stereoscopy
(*f*) confocal optical microscope

2-3.2.3 Reference. See Section 5 and 8, and Nonmandatory Appendix C and E of this Standard.

2-3.3 Type III: Scanned Probe Microscopes

2-3.3.1 Properties

(*a*) measuring range most often includes smooth surfaces
(*b*) measures roughness with respect to an external datum
(*c*) may have a selection of filters and parameters for data analysis
(*d*) probe tip sizes and scanning rates influence lateral resolution, which varies from atomic scale to micrometers
(*e*) can generate filtered or unfiltered profiles
(*f*) capable of either unfiltered profiling or topographic analysis (area profiling), or both
(*g*) results may be sensitive to steep surface slopes and, for STM, to surface conductivity

2-3.3.2 Examples

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

2-3.3.3 Reference. See Section 5 and Nonmandatory Appendix E of this Standard.

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 μm or less. With a 10 μm stylus radius, the

instrument may not be suitable for measuring very short spatial wavelengths

(d) 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. See Section 4 of this Standard.

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) typically produce measurements of the *Ra* parameter, but other parameters may also be available.

(c) for those instruments using a diamond stylus, the stylus tip radius is commonly 10 μm but may be smaller. With a 10 μm stylus radius, these instruments may not be suitable for measuring very short spatial wavelengths.

(d) 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. See Section 4 of this Standard.

2-3.6 Type VI: Area Averaging Methods

2-3.6.1 Properties

(a) Measures 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. See Section 6 of this Standard.

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

3-1 Scope

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 3274-1996 is also included. In cases of disagreement regarding the interpretation of surface texture measurements, a Type I instrument in compliance with ISO 3274-1996 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

The following is a list of standards and specifications referenced in this Standard, showing the year of approval.

ISO 3274-1996, Geometrical Product Specifications (GPS) — Surface Texture: Profile Method — Nominal Characteristics of Contact (Stylus) Instruments

ISO 4288-1996, Rules and Procedures for the Measurement of Surface Roughness Using Stylus Instruments

Publisher: International Organization for Standardization (ISO), 1 ch. de la Voie-Creuse, Case Postale 56, CH-1211, Genève 20, Switzerland/Suisse (www.iso.org)

See also Sections 1, 2, 9, and 11 of this Standard.

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. The stylus is traversed along the surface a distance termed the traversing length to allow for an adequate evaluation length and number of cutoff lengths for the measurement (see para. 1-3.5). Selection of the various measurement lengths is described in para. 3-3.20. 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 the 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. The tip geometry should be specified in all measurements of critical importance. Refer to Section 9 (Table 9-2) for stylus tip size selection when the short wavelength cutoff is specified. Basic tip geometries are described in paras. 3-3.4.2 and 3-3.4.3.

3-3.4.2 Conical Stylus With Spherical Tip. The conical stylus with a nominal spherical tip is most commonly used. It incorporates an included flank angle (α) which is typically 60 deg or 90 deg (see Fig. 3-2). The effective radius (R) of the tip shall be 2 μm, 5 μm, or 10 μm (0.00008 in., 0.0002 in., or 0.0004 in.). Effective radius 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 30 deg (for a 60-deg stylus) or 45 deg (for a 90-deg stylus), either side of this bisector. The arcs and the radii must contain the stylus tip profile.

The tip radius of the stylus shall be within ±30% of the nominal value. This can be evaluated as shown in Fig. 11-7 of Section 11. Because the stylus tip is subject to wear and mechanical damage, even when made of diamond, regular checks of the stylus are recommended.

Fig. 3-1 Profile Coordinate System

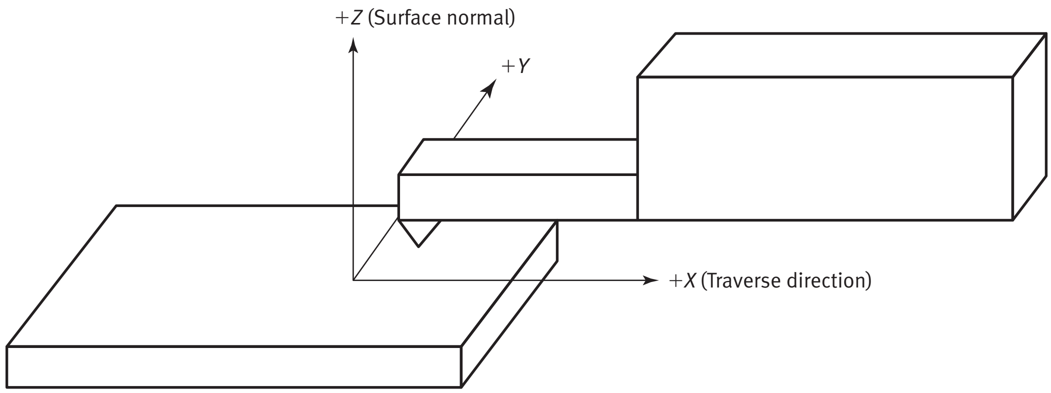
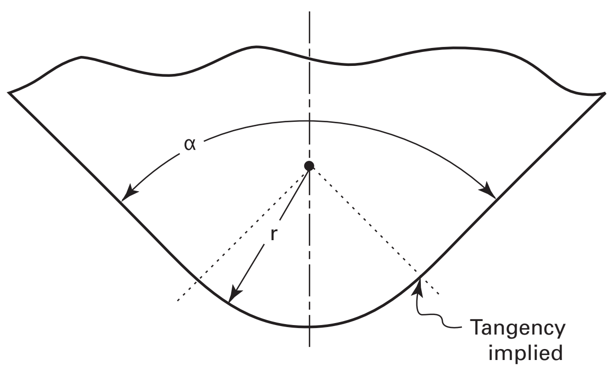
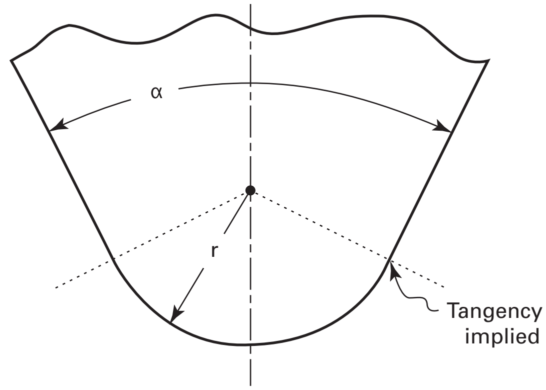


Fig. 3-2 Conical Stylus Tip

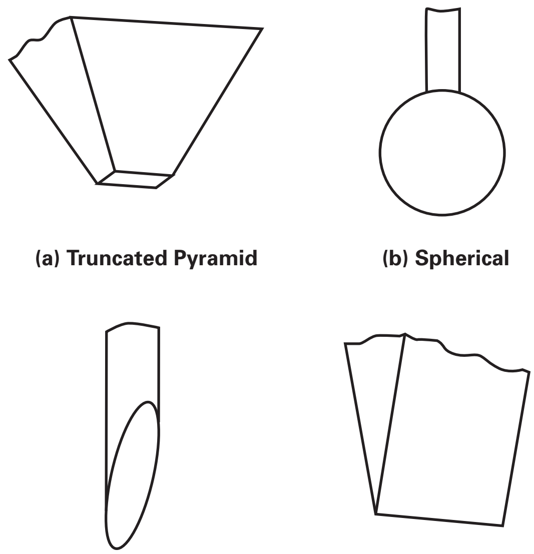


(a) Conical Stylus With Spherical Tip – Included Angle 90 deg



(b) Conical Stylus With Spherical Tip – Included Angle 60 deg

Fig. 3-3 Other Stylus Tip Geometries



(a) Truncated Pyramid (b) Spherical

(c) Chisel Point (d) Chisel (Knife) Edge

This is to ensure that the tip radius is within the tolerances stated above.

The stylus condition should be checked on a regular basis, determined by the amount of use, wear, environment, instrument type, required accuracy, and application, etc. Techniques for checking the stylus condition are discussed in Section 11.

3-3.4.3 Other Stylus Tip Geometries. Other stylus tip geometries are appropriate for particular measurement applications (Fig. 3-3). Tip geometry must be explicitly specified when alternate stylus tips are used.

(a) Truncated Pyramid Tip. A truncated pyramid stylus with a rectangular contact area and an included flank angle (α) in the direction of traverse typically of 60 deg or 90 deg.

(b) Spherical Tip. A large radius ball tip (e.g., 1 mm radius ruby ball) may be used for "large scale" roughness measurements of surfaces such as roadways, etc. (e.g., traverse lengths greater than 25 mm, peak-to-valley amplitudes greater than 50 μm).

(c) Chisel Point Stylus. A stylus tip constructed from a cylinder sliced at a shallow angle. It is typically used for measuring large step heights (e.g., 1 mm height) and general form measurements.

(d) Chisel (Knife) Edge Stylus. A stylus with a line contact perpendicular to the direction of traverse. It is typically used for measuring cylindrical surfaces in the axial direction to minimize alignment errors. It can also be used to measure the maximum amplitude of area peaks, which otherwise may be missed by styli with a point contact.

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 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. To ensure that the stylus accurately follows the surface being measured, a contacting force normal to the surface is required to maintain stylus tip contact with the surface. The static measuring force is the force exerted on the workpiece surface by the stylus while at rest. When specifying an instrument, the static measuring force is given at the midpoint of the height (z) range of the instrument.

3-3.5.2 Maximum Recommended Static Measuring Force. The stylus force should be sufficient to maintain top-surface contact but not so large that the stylus causes damage to the surface. The maximum recommended values of static measuring force are determined by the stylus radius, and are given in the following in-text table:

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

For a truncated pyramid stylus, use the smaller of the dimensions of the truncated flat as the nominal tip radius.

On soft materials, the stylus may make a visible mark as it traverses the surface. Such a mark does not necessarily mean that the measurement is incorrect. In some cases, it may be desirable to make measurements using a noncontact technique.

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 with amplitude and spatial wavelength of the surface irregularities, stylus location on the surface, and the instrument traversing speed.

3-3.5.5 Total Stylus Force. In all cases, a minimum total stylus force (static and dynamic) should be applied to maintain contact with the surface during measurement to avoid situations in which the stylus leaves the surface during traverse.[1]

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 the 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.

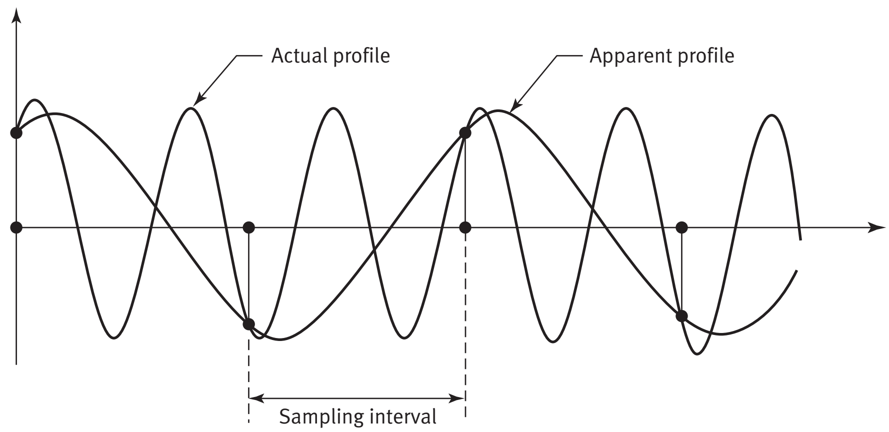
3-3.8 Analog-to-Digital Conversion. This Section, covering analog to digital conversion, is optional for Type I instruments according to the classification scheme of Section 2, which covers both analog and digital instruments. However, this Section covers terminology associated with the digitization and storage of profile data which is a requirement if an instrument is to comply with ISO 3274-1996.

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

[1] J.F. Song, T.V. Vorburger, "Stylus Flight in Surface Profiling," *Transactions Journals of the ASME*, Vol. 118, May 1996, Page 188.

Fig. 3-4 Aliasing



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

3-3.14 Instrument *z* Range-to-Resolution Ratio. The instrument z range-to-resolution ratio is the ratio of total z axis measuring range to the instrument measuring z 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 the profile which is generated by internal and external mechanical disturbances as well as by deviations 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 shortwave 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

Table 3-1 Cutoff Values for Periodic Profiles Using *RSm*

RSm							
Over		Up to (Including)		Cutoff Length		Typical Evaluation Length	
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)

GENERAL NOTE: This table differs from the B46.1-2002 edition and is now realigned with ISO 4288-1996.

(*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. Roughness filter cutoff length is determined in part by the *x* and *z* aspects of the surface under evaluation as related to the intended function of the surface. The roughness filter cutoff length should be chosen by the designer in light of the intended function of the surface. When choosing the appropriate roughness filter cutoff, one must be cognizant that the surface features not measured within the roughness cutoff bandwidth may be quite large and may affect the intended function of the surface. Thus in some cases it may be necessary to specify both the surface roughness and surface waviness and their respective cutoff lengths.

The roughness long-wavelength (λc) and short-wavelength (λs) cutoffs must be specified, and should be indicated on the drawing per ISO 1302:2002. When the roughness cutoff is not specified, guidelines are given below for measurement of periodic and nonperiodic profiles based on estimates of *RSm* and *Ra*, respectively. These guidelines are intended to include the dominant features of a surface in the measurement whether these surface features are relevant to the function of the surface or not.

3-3.20.1 Profile Filter Cutoff Selection For Periodic Profiles

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

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

3-3.20.2 Profile Filter Cutoff Selection For Nonperiodic Profiles

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

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

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

(*d*) If the measured *Ra* 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 *Ra* at this shorter cutoff length. If this shorter cutoff length is acceptable in terms of the resultant *Ra*, then this becomes the measurement cutoff. If this new cutoff length and *Ra* combination do not conform to Table 3-2, then the cutoff length determined in para. 3-3.20.2(d) should be used.

3-3.20.3 Profile Filter Evaluation Length. Typically the evaluation length is chosen to include at least five roughness long-wavelength cutoff lengths (λc). However, depending on the size of the measurement area, it may be necessary to limit the evaluation length to include less than five roughness cutoff lengths (λc). In this case, the evaluation length used should be noted on the appropriate documentation. Some instruments may automatically change the roughness long-wavelength cutoff to maintain five cutoff lengths within the evaluation length. Therefore, care must be taken to ensure that the proper roughness cutoff length (λc) is 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.

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.

Table 3-2 Cutoff Values for Nonperiodic Profiles Using *Ra*

Ra							
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)	0.25	(0.010)	1.25	(0.05)
0.10	(4.0)	2.0	(80.0)	0.80	(0.03)	4.0	(0.16)
2.0	(80.0)	10.0	(400.0)	2.5	(0.10)	12.5	(0.5)
10.0	(400.0)	. . .	. . .	8.0	(0.3)	40.0	(1.6)

3-3.21.3 Magnification Ratio (Aspect Ratio). The magnification ratio or aspect ratio is the ratio of the *z*-axis magnification to the *x*-axis magnification.

3-3.22 Profile Evaluation. The evaluation of the primary roughness and waviness profiles shall be according to 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, if 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 the SI unit of length. This specimen should also be clean and free from signs of wear, which may affect the calibration of the instrument. Measurements of the precision reference specimen must be within the stated uncertainty of the precision reference specimen.

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 *Ra*, the value can be obtained after proper filtering.

Section 4
Measurement Procedures for Contact, Skidded Instruments

4-1 Scope

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.

Depending upon the effective size of the skid relative to the surface spatial wavelengths and amplitudes to be measured, waviness may not be accurately measured with a skidded instrument. Therefore it is generally recommended that waviness be measured with a skidless instrument.

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

The following is a list of standards and specifications referenced in this Standard, showing the year of approval.

ISO 1302:2002, Geometrical Product Specifications (GPS) — Indication of Surface Texture in Technical Product Documentation

Publisher: International Organization for Standardization (ISO), 1 ch. de la Voie-Creuse, Case Postale 56, CH-1211, Genève 20, Switzerland/Suisse (www.iso.org)

See also Sections 1, 2, 3, 9, and 11 of this Standard.

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

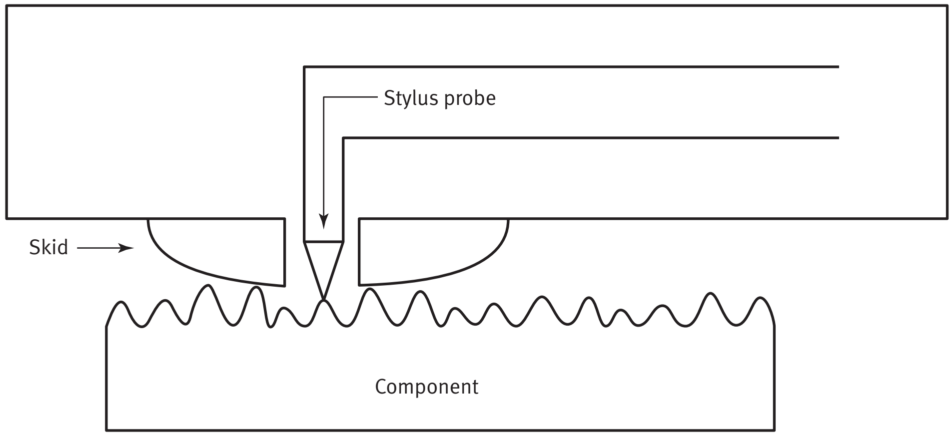
4-4.1 Roughness Average Value *Ra* From Averaging and Digital Readout Instruments

(a) The readout device shall display the average deviation from the filtered mean line in μm (μin.). This quantity is the roughness average *Ra*, 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.

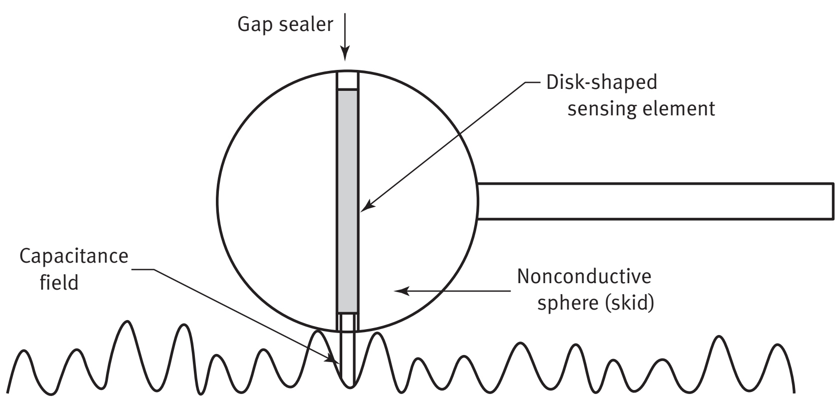
(b) For uniform interpretation of readings from contact type instruments of the averaging type, it should be understood that the reading which is considered significant is the mean reading around which the value tends to dwell or fluctuate with a small amplitude. Analog meters are damped to minimize 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.

4-4.2 Cutoff Selection. In all cases, the cutoff (λc) must be specified on drawings created or revised after December 14, 1996, 6 months after the 1995 revision of this Standard was published. On prior drawings when the cutoff was not specified, the 0.8 mm (0.03 in.) value was applied. 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.

Fig. 4-1 Schematic Diagrams of a Typical Stylus Probe and Fringe-Field Capacitance Probe



(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 nonconductive sphere. The sensor is concentric with the equator of the sphere, but is uniformly offset from the sphere edge.

(b) This figure 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.

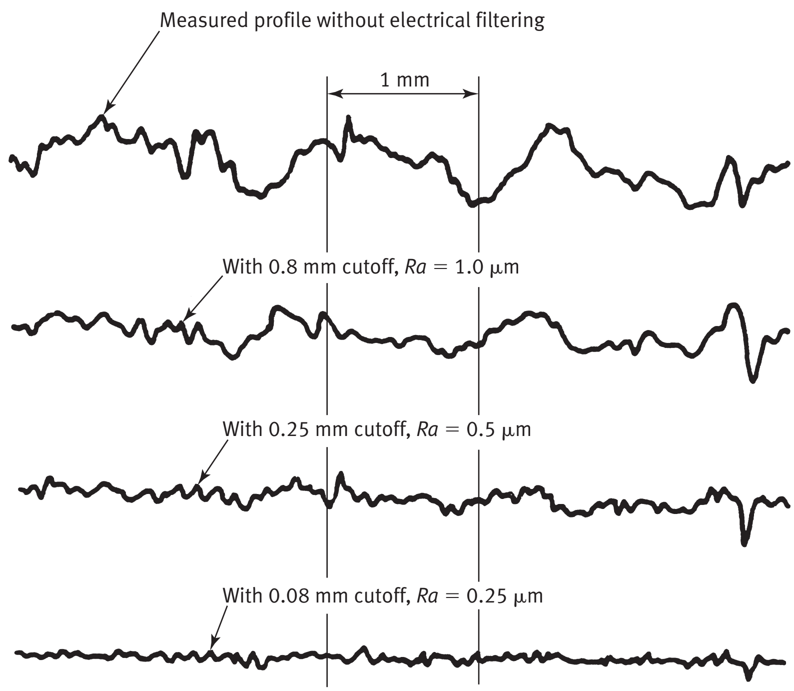
Table 4-1 Measurement Cutoffs and Traversing Lengths for Continuously Averaging Instruments Using Analog Meter Readouts

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	6.0–20.0

Table 4-2 Measurement Cutoffs and Minimum Evaluation Lengths for Instruments Measuring Integrated Roughness Values Over a Fixed Evaluation Length

Cutoff		Measurement 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	0.3	24.0	0.9

Fig. 4-2 Effects of Various Cutoff Values



GENERAL NOTE: Profiles have unequal vertical and horizontal magnifications.

4-4.3 Response Time for Analog Averaging Instruments. 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 ν (i.e., $f_c = \nu/\lambda c$).

4-4.4 Traversing Length for Analog Averaging Instruments. 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. Care must be taken to ensure that the cutoff length is chosen appropriately (see para. 3-3.20) and that a suitable traversing length is selected. Typically, the region being measured is chosen to permit a minimum travel in one direction of five times the cutoff length. Traversing lengths less than five cutoffs may be necessary as a result of sample size and should be noted as appropriate on drawings or test documents.

4-4.5 Stylus Probe

4-4.5.1 Stylus Tip. Refer to para. 3-3.4.

4-4.5.2 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 designs, the skid is concentric with the probe. The arrangement of skids, 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 μm (500 μin.) *Ra*. 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.

(d) Situations in which the skid leaves a mark on the surface may have adversely affected the measurement results. Therefore, noncontact measurement techniques should be considered.

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 μm 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.

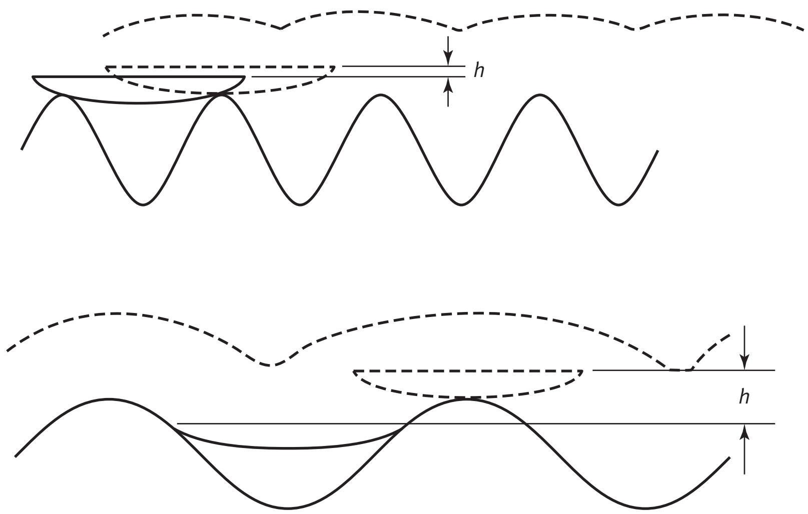
4-4.7 Possible Sources of Skid Errors. If the skids undergo appreciable vertical displacement in moving over a surface, this displacement is subtracted from the probe motion (see Fig. 4-3). This displacement is dependent on the skid location and the wavelength of the surface waviness. In some cases smaller 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 *Ra* 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 ±7% from the true *Ra* value of the input.

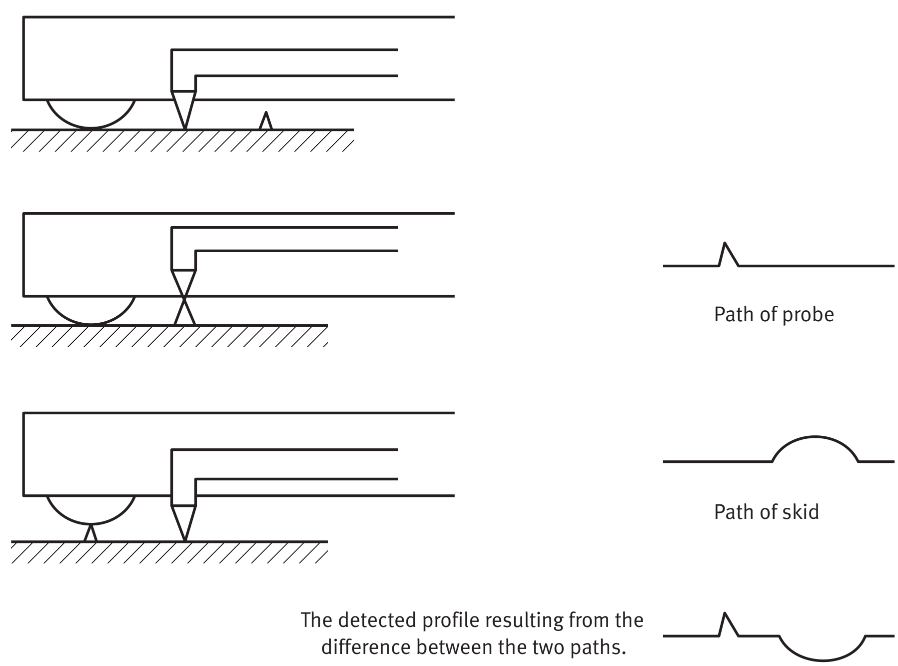
4-4.9 Operational Accuracy. Instrument calibration for *Ra* measurement should be checked using precision roughness specimens at one or two points in the measurement range depending on the manufacturer's instructions. If two precision reference specimens are used, one should be characterized by a large *Ra* for checking calibration and the second by a small *Ra* for checking linearity. *Stylus check* specimens should not be used for this purpose. If the *Ra* 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.

Fig. 4-3 Examples of Profile Distortion Due to Skid Motion



GENERAL NOTES:
(a) This figure 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. 4-4 Examples of Profile Distortion



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

Section 5
Measurement Techniques for Area Profiling

5-1 Scope

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 Type II or III or modifications of Type I instruments. The instrument types are discussed in Section 2.

5-2 References

The following is a list of standards and specifications referenced in this Standard, showing the year of approval.

ISO 1302:2002, Geometrical Product Specifications (GPS) — Indication of Surface Texture in Technical Product Documentation

Publisher: International Organization for Standardization (ISO), 1 ch. de la Voie-Creuse, Case Postale 56, CH-1211, Genève 20, Switzerland/Suisse (www.iso.org)

See also Sections 1 and 2 of this Standard.

5-3 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 *Sa* and *Sq*. 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 *Sa* and *Sq*, 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 ISO 1302:2002 do not apply entirely to this class of instruments.

5-4 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.

5-5 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. Nonmandatory Appendix E describes operating principles for several types of area profiling techniques.

Section 6
Measurement Techniques for Area Averaging

6-1 Scope

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 paras. 1-5 and 1-6. 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. Nonmandatory Appendix F describes operating principles for these area averaging methods.

Section 7
Nanometer Surface Texture and Step Height Measurements by Stylus Profiling Instruments

7-1 Scope

This Section of the B46.1 standard is concerned with the measurement of very small (nanometer-sized) features on surfaces. These features may be either irregular, such as roughness and waviness features, or regular, such as the depths of etched grooves or the thicknesses of deposited films. Because these very small features are at (or near) the performance limit of many metrology instruments, special recommendations are made for both the measurement methods and the reports for these measurements. Observing the recommendations of this Section will reduce the uncertainty of measuring very small features and will improve the comparison of results from different laboratories.

7-2 Applicable Documents

Guide to the Expression of Uncertainty in Measurement, 1995 (Referenced in the text as GUM)

Publisher: International Organization for Standardization (ISO), 1 ch. de la Voie-Creuse, Case Postale 56, CH-1211, Genève 20, Switzerland/Suisse (www.iso.org)

7-3 Definitions

7-3.1 Step Height, *Zs*. The distance between the upper and lower portions of a step-height specimen, measured perpendicular to the surface. Different step-height algorithms may be applied depending on the geometry of the specimen and the methods used to measure it. For example, the specimen geometry may consist of a single-sided step or a double-sided step or an array of steps whose heights are to be averaged. The measurement may be accomplished with a profiling method or an area profiling method.

7-3.2 Noise. The cyclic variation in the measured value of a feature having unchanging size. The cyclic variation may be simple (as the sine wave of simple harmonic motion) or complex (as the combining of numerous sine waves of differing frequency and amplitude). The cyclic nature of noise distinguishes it from zero point drift.

7-3.3 Type A Evaluation (of Uncertainty). Method of evaluation of uncertainty by the statistical analysis of a series of observations (GUM).

7-3.4 Type B Evaluation (of Uncertainty). Method of evaluation of uncertainty by means other than the statistical analysis of a series of observations (see GUM).

7-3.5 Standard Uncertainty. Uncertainty of the result of a measurement expressed as a standard deviation (GUM).

7-3.6 Combined Standard Uncertainty. Standard uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities, equal to the positive square root of a sum of terms, the terms being the variances or covariances of these other quantities weighted according to how the measurement result varies with changes in these quantities.

7-3.7 Expanded Uncertainty. Quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand (see GUM).

7-3.8 Coverage Factor, *k*. Numerical factor used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty.

NOTE: For quantities discussed here, a coverage factor, *k*, of 2.0 shall be used.

7-4 Recommendations

7-4.1 Instruments

7-4.1.1 Instrument Vertical Resolution. The vertical resolution of the instrument should be small with respect to the size of the feature that is to be measured, typically less than $\frac{1}{10}$ of the roughness parameter or step height to be measured.

7-4.1.2 Instrument Spatial Resolution. The spatial resolution of the instrument shall be shorter than the short wavelength cutoff, λs.

7-4.1.3 Stylus Cone Angle. The stylus cone angle shall be sufficiently small that the cone flank does not come into contact with the surface feature being measured.

7-4.1.4 Noise and Zero Point Drift. The uncertainty arising from noise and zero point drift in the instrument must be small with respect to the size of the feature to be measured.

7-4.2 Methodology

7-4.2.1 Number of Data Points. A sufficient density of data points must be collected to provide an accurate sampling of the shortest spatial wavelengths to be assessed in the surface profile. The shortest spatial wavelengths of interest should be at least five times larger than the sampling interval (point spacing). This recommendation ensures a minimum peak amplitude estimate accuracy of 90% for the shortest spatial wavelengths.[1, 2]

NOTE: If the peak-to-valley amplitude of a cosine wave is 1.0 and the number of sampled points per wavelength is N it may be shown that the smallest detected peak-to-valley amplitude "a" is given by the following:

$$a = [1 + \cos(\pi/N)]/2$$

For smaller integer values of N, the smallest detected peak-to-valley amplitude is given in the following table:

N	2	3	4	5	6	7	8
a	0.50	0.75	0.854	0.905	0.933	0.950	0.962

7-4.2.2 Curvature (Form) Removal. Many surfaces include a designed form or curvature because of their intended function. The underlying curvature or form of the surface may be removed from the data. If curvature or form removal procedures are used, they shall be reported in accordance with para. 7-7.2.2.

7-4.2.3 Measurement of Step Heights and Groove Depths. All double-sided step heights and groove depths, including samples to be measured and calibration standards, shall be evaluated using the procedure described in Section 11 as a guide. For single-sided steps, different methods must be used but the algorithms are not yet standardized. The algorithm used to determine the height or depth shall be reported.

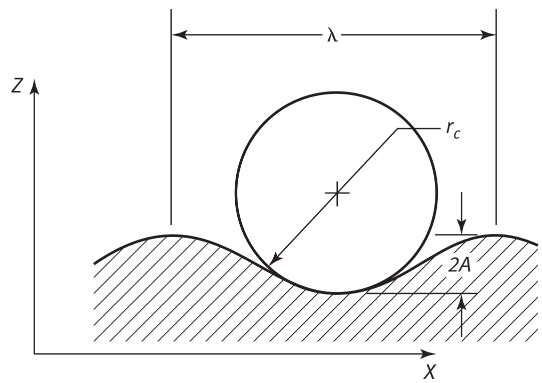
7-4.2.4 The Maximum Stylus Tip Radius, $r_{max.}$, for Roughness. The detection and accurate measurement of nanometer sized surface features require stylus tips with small radii. The stylus tip radius r acts as a short wavelength cutoff filter with special characteristics. Consider a surface profile which is a sine wave of the form as follows:

$$z = A \sin(2\pi x/\lambda),$$

as shown in Fig. 7-1.

The radius of curvature r_c at the top and bottom of the wave form is as follows:

Fig. 7-1 The Radius of Curvature for a Surface Sine Wave



$$r_c = \lambda^2/(4\pi^2 A)$$

This is the radius of the largest sphere that can follow the profile of the sine wave surface. Larger radii will not fit into the bottoms of the valleys in the sine wave. If the sphere represents the tip of the stylus on a measuring instrument the stylus can sense the full amplitude of the sine wave surface only if the stylus tip radius is less than or equal to r_c. For stylus radii larger than r_c, the peak-to-valley amplitude of the surface wave is attenuated and the degree of attenuation is greater as the stylus tip radius increases. Conversely, a stylus tip radius, r_c, acts as a short wavelength filter that attenuates sine wave surface features at wavelengths shorter than λ calculated from the following:

$$\lambda = (4\pi^2 A r_c)^{1/2}$$

Further, since the rms value of a sine wave surface, Rq is the amplitude A divided by $2^{1/2}$, it follows that:

$$r_{max} = \lambda^2/(4 \cdot 2^{1/2}\, \pi^2 Rq)$$

where Rq is the rms roughness parameter of the sine wave surface and r_{max} is the maximum radius of the stylus tip for the sine wave surface. Tip radii larger than r_{max} will not be able to sense the full amplitude of surface wavelengths shorter than λ.

For surface profiles other than sine waves, the size of the maximum tip radius (the largest tip radius that can sense the full amplitude of the surface form) may vary from that derived above but the principle still applies: for any surface there is a maximum tip radius size, r_{max}, such that for styli with radii greater than r_{max} the measured peak-to-valley amplitude is attenuated. Knowledge of the shape of the surface profile is helpful in selecting the appropriate stylus tip radius. Conversely, knowledge of the stylus tip is helpful in determining the short-wavelength limits of measured surface profiles.

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[1] "Interpolation With Splines and FFT in Wave Signals," Sanchez Fernandez, L. P., *Research in Computing Science*, Vol. 10, 2004, pp. 387–400.

[2] "Measurement Error of Waves in Research Laboratories" (Spanish language), Sanchez Fernandez, L. P., *Hydraulic Engineering in Mexico*, Vol. XIX, No. 2, 2004, pp. 101–106.

Fig. 7-2 Stylus Tip Touching Bottom and Shoulders of Groove

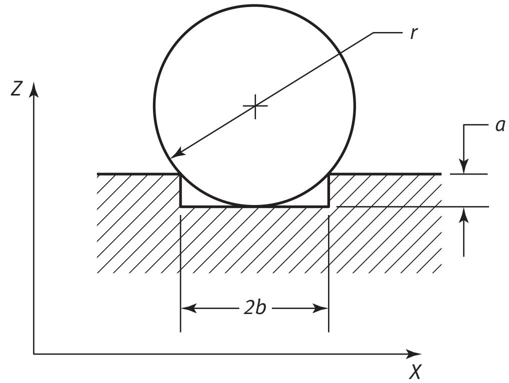
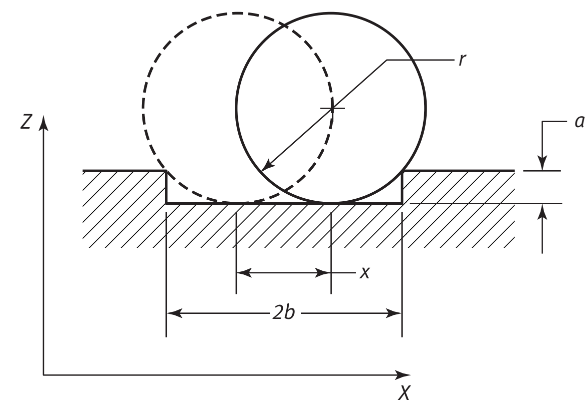


Fig. 7-3 The Stylus Tip Contact Distance, *x*



7-4.2.5 The Maximum Stylus Tip Radius, r_{max}, for Grooves. When measuring a narrow negative step, a groove, it may be necessary to choose a small stylus tip radius and small cone angle to ensure that the tip contacts the bottom of the groove (See Fig. 7-2). If the groove depth is small enough that the groove shoulders contact only the spherical tip and not the cone flank, the maximum tip radius *r* that will reach the bottom of the groove is as follows:

$$r = a/2 + b^2/2a,$$

where *a* is the groove depth and *b* is one-half the groove width as shown in Fig. 7-2.

With a tip radius smaller than $(a/2 + b^2/2a)$ the spherical tip will contact the bottom of the groove over a distance *x* given by:

$$x = 2b - 2(2ra - a^2)^{1/2},$$

as in Fig. 7-3.

It is recommended in Section 11 that a step height or a groove measurement use the data from the middle third of the groove as follows:

$$x = 2b/3$$

Assuming that the width between the upper groove shoulders defines the width of the measured groove, that implies a maximum tip radius, r_{max}, given by the following:

$$r_{max} = 2b^2/9a + a/2$$

Accurate measurement of narrow negative steps (grooves) requires careful coordination of all the factors affecting spatial resolution. These factors include the stylus tip radius, the short wavelength cutoff filter and the horizontal sampling interval.

7-4.2.6 Stylus Force. The stylus force must be selected

(*a*) to be high enough to maintain the stylus tip in contact with the surface being measured, and

(*b*) to be low enough to avoid damaging the surface by scratching or gouging it

The suitability of the stylus force may be tested by running the measurement at a chosen scan speed and sampling interval and again at half the scan speed and the same sampling interval; if the measurement is unchanged the stylus force is acceptable.

7-4.3 Environment. The instrument's installation and setup shall minimize environmental influences on a measurement.

7-5 Preparation for Measurement

7-5.1 Instruments

7-5.1.1 Maintain the instrument according to the manufacturer's instructions in order to ensure performance to specification. Allow the instrument to come to mechanical and thermal equilibrium with its environment before attempting to make measurements.

7-5.1.2 Test the stylus condition either by observing its expected performance, by viewing it under a high power microscope or by scanning it over the edge of a razor blade (see Section 11). Replace the stylus if it is damaged or no longer has its original shape.

7-5.1.3 Verify that the instrument can support the sample in a stable position.

7-5.1.4 Verify that both the sample surface and stylus are free of contamination.

7-5.2 Environment. Review potential contributors to noise and drift. Adjust the source of disturbances (windows, doorways, air conditioners, foot traffic, the number of people in the vicinity of the instrument, acoustic noise levels, etc.) to minimize their effects. Permit the instrument to reach equilibrium with this new environment.

7-6 Calibration Artifacts

For the purposes of this Standard, a calibration artifact must carry with it a size value, such as a step height, and an uncertainty estimate, both traceable to the SI unit of length. The uncertainty estimate must be consistent with the GUM. This Section describes three kinds of calibration artifacts. Other kinds of artifacts are acceptable if they may be adapted to the metrology procedures described herein. Vertical scale calibration in the nanometer range using roughness specimens is not recommended.

7-6.1 Calibration Specimens. Vertical scale calibration may be accomplished with a step height calibration specimen. Step height calibration specimens used in nanometer metrology shall be Type A1 specimens in accordance with Section 11.

Step height calibration specimens are solid substrates, often of glass or silicon, on which the surface has been specially prepared and conditioned (by deposition, oxidation, etching, and/or some other combination of processes) to provide a durable and uniform surface finish with calibrated height features such as step heights or grooves. The surface finish and/or features may be measured and characterized with calibrated profiling techniques. Their uniformity and durability permit them to retain their calibration in service for long periods of time.

Step height calibration specimens are avaialable in sizes from approximately 7.0 nm to many micrometers in height.

7-6.1.1 Specimen Storage and Cleaning. The surfaces of standard specimens are vulnerable to damage and must be handled and stored in a manner that will avoid contact with the surface. Should the standard require cleaning, special techniques should be used to prevent damage.

7-6.2 Calibrated Displacement Actuators. Calibrated displacement actuators are vertical scale calibration devices which are driven by electrical currents and are capable of stable and repeatable displacements. They may be calibrated with respect to the wavelength of light with an interferometer. If sufficiently stable and linear, they can therefore provide displacements in the nanometer size range that are traceable to the SI unit of length. They may also be calibrated on surface profilometers, which are themselves suitably calibrated.

Such actuators may provide static displacements for use in step height calibrations or dynamic displacements for roughness calibrations, depending upon the form of the current supplied to the actuator.

7-6.2.1 Calibrated Displacement Actuator Storage and Cleaning. In order to promote stability a calibrated displacement actuator should be stored in a padded instrument case. It should not be subject to extreme temperatures, high humidity, especially condensation on the case or the actuator, or high shock loads. It must be otherwise maintained according to the manufacturer's instructions.

7-6.3 Ultrasmooth Surface Artifacts. Ultrasmooth surface artifacts are not used for scale calibration but rather for testing the noise floor of a surface measuring instrument. They are available from optical fabrication shops. The rms roughness Rq may typically range from 0.1 nm to several nanometers.

7-6.3.1 Ultrasmooth Surface Artifact Storage and Cleaning. The surfaces of ultrasmooth artifacts are vulnerable to damage and must be handled and stored in a manner that will avoid contact with the surface. Should the standard require cleaning, special techniques should be used to prevent damage.

7-6.4 Artifact Calibration Requirements. The calibration procedure shall provide the information required in paras. 7-6.4.1 through 7-6.4.3.

7-6.4.1 Calibration specimens shall be calibrated using Section 11 as a guide. Uncertainty shall be estimated according to the GUM.

7-6.4.2 Calibrated displacement actuators shall be calibrated with interferometers or calibrated profiling instruments using the manufacturer's instructions as a guide. Uncertainty shall be estimated according to the GUM.

7-6.4.3 The roughness of super-flat surface artifacts shall be calibrated using profiling techniques. Uncertainty shall be estimated according to the GUM.

7-7 Reports

7-7.1 Data. As a minimum, measurements made in accordance with this Section shall contain the seven data statements shown in the following:

(a) the I.D. of the sample measured
(b) the measured property
(c) the measured value
(d) the expanded uncertainty ($k = 2$) of the measurement
(e) transmission band (λs and λc)
(f) date and time
(g) name of metrologist

7-7.2 Annotations to the Data

7-7.2.1 Zero Point Drift Correction. If apparent zero point drift has been removed, the measured value shall be followed by the word "Leveled."

7-7.2.2 Curvature (Form) Removal. If form or curvature has been removed, the measured value shall be followed by the words "Form removed."

7-7.2.3 Other Data Processing Procedures. If any data processing techniques have been used that are not in accordance with the GUM, the measured uncertainty shall be followed by the words "Other than GUM."

7-7.2.4 Non-Statistical Estimates of Uncertainty. If the uncertainty estimate is not based entirely upon test data (at all levels), the measurement uncertainty shall be followed by the phrase "includes Type B components."

7-7.3 Reporting Example

(a) Sample: AX55654-A
(b) The Measured Property: *Ra*
(c) The Measured Value: 12.24 nm, Leveled
(d) The Expanded Uncertainty ($k = 2$) of the Measurement: 0.84 nm, includes Type B components
(e) Transmission Band: 0.5 μm to 1200 μm
(f) Date and Time: Dec, 12, 1999, 4:55 PM
(g) Name of Metrologist: John Smith

Section 8
Nanometer Surface Roughness as Measured With Phase Measuring Interferometric Microscopy

8-1 Scope

This Section describes instruments for the measurement of surface roughness in the range of 0.1 nm to 100 nm *Rq* using the technique of phase measuring interferometric microscopy. This Standard addresses procedures for measurement of surface *Rq* along a single profile. Other surface parameters may also be measured if available.

This Section is limited to surfaces that offer sufficiently uniform optical properties consistent with the high precision characteristics listed under instrument requirements. This Section is not concerned with the specification of precision reference specimens.

8-2 Description and Definitions: Noncontact Phase Measuring Interferometer

The basic instrument (Fig. 8-1) consists of an interferometer integrated with a microscope. Within the interferometer, one beam of light travels down a reference path, which includes a number of optical elements including an ideally flat and smooth mirror from which the light is reflected. Another beam of light travels to and is reflected from the sample being tested. When the two beams of light are combined, an image of the test surface is formed at the detector array, superimposed with a series of dark and bright bands of light, defined as fringes. During measurement, the reference mirror is translated to cause a known difference between the optical path to the test surface and the optical path to the reference mirror.

By measuring the intensity pattern from the various images during the shifting process, the phase variation of the wavefront, Φ, returning from the specimen may be measured. Given that the variation Φ_i is a function of camera element i, the actual surface height Z_i at the i'th location is determined by the following equation (Creath 1988).

$$Z_i = \lambda \Phi_i / 4\pi \tag{1}$$

where λ is the wavelength of illumination.

The height Z_i at each detector array element is calculated and then *Rq* is calculated.

The longest spatial wavelength of the profile that may be measured, λL is given by the following:

$$\lambda L = N\Delta / M \tag{2}$$

where M is the magnification of the optical system, Δ is the spacing of the elements in the detector array, and N is the total number of array elements in the detector (Fig. 8-2).

The shortest spatial wavelength (Fig. 8-3) that may be measured λR, depends on the nature of the optical system being used (Hetch and Zajac 1976). As an approximation, if the lateral resolution of the instrument is limited by the optical system's resolution, then λR is given by the following:

$$\lambda R = 5d \tag{3}$$

where d is the optical resolution of the system and is given by the Sparrow (Hetch and Zajac 1976) criterion as follows:

$$d = \lambda / (2NA) \tag{4}$$

where λ is the wavelength of the illumination, and NA is the numerical aperture of the objective lens.

If the lateral resolution is limited by the geometric spatial sampling of the detector system (Sanchez 2004) (Sanchez 2004), then λR is as follows:

$$\lambda R = 5\Delta / M \tag{5}$$

where Δ is the spacing of the detector pixels and M is the magnification of the optical system.

8-3 Key Sources of Uncertainty

Sources of uncertainty include such items as temperature and humidity fluctuations, electronic noise sources throughout the instrumentation, and vibration sources. For reliable measurement in the nanometer regime, the height resolution (Nonmandatory Appendix E) must be less than $\frac{1}{10}$ of the *Rq* of the surface to be measured.

8-4 Noncontact Phase Measuring Interferometer Instrument Requirements

8-4.1 Tilt Adjustment. The instrument must contain elements that will allow the precise control of the relative tilt of the specimen surface to the reference path. The instrument must allow the tilt to be adjusted to easily produce $\frac{1}{10}$ of a fringe across the field of view.

8-4.2 Sample Stage. The stage that supports the specimen must translate in minimal increments consistent with the correlation length of the sample.

Fig. 8-1 A Typical Phase Measuring Interferometer System

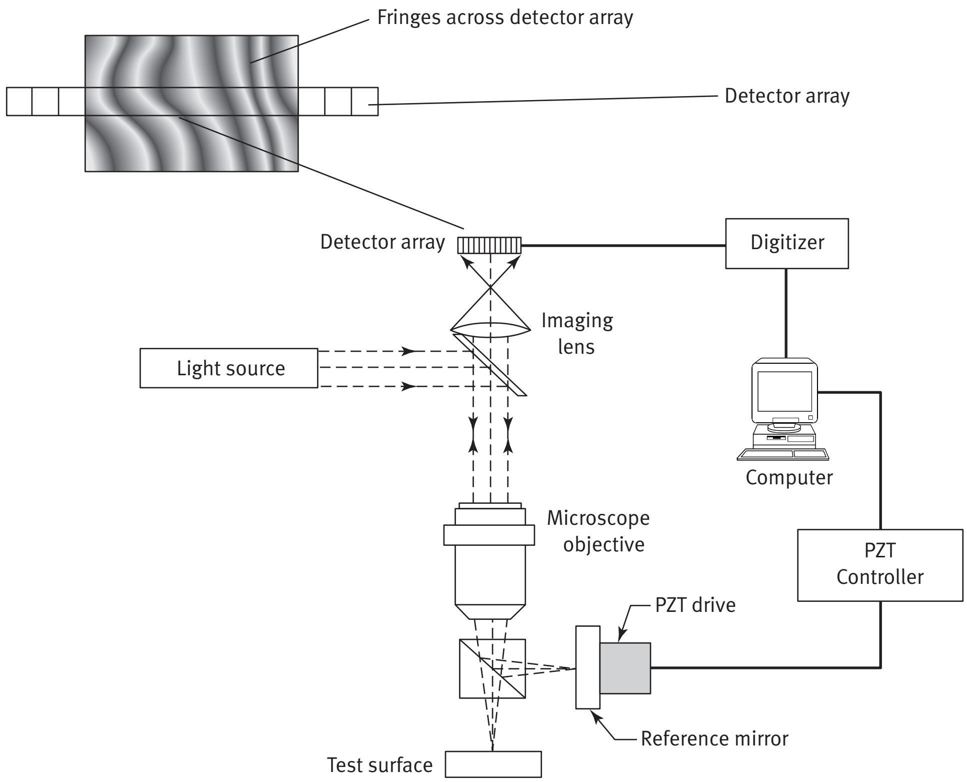


Fig. 8-2 Demonstration of the Detector Array With Element Spacing Δ and the Measurement of the Longest Spatial Wavelength, *λL* Covering the Total Number (*N*) Pixels

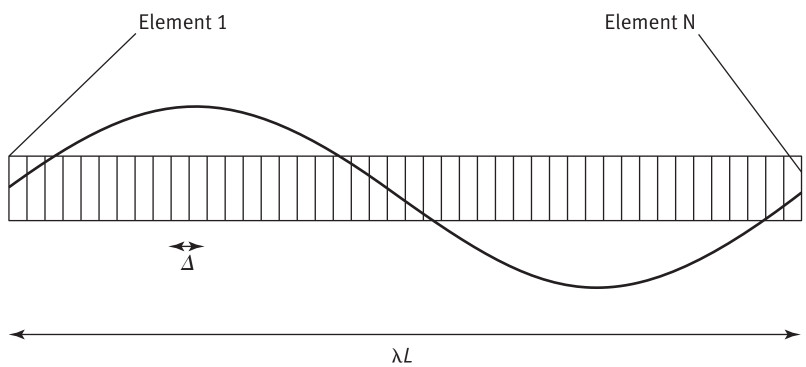
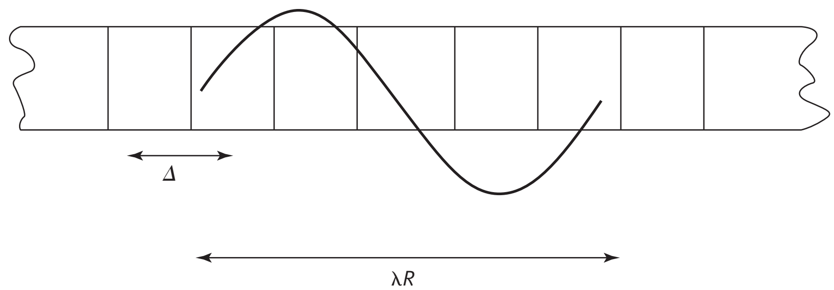


Fig. 8-3 Demonstration of the Detector Array With Element Spacing Δ and the Measurement of the Smallest Spatial Wavelength, λR Covering Five Pixels



8-4.3 Focusing Means. The system must contain means that will allow the precise control and verification of the focus of the system. The rms repeatability of the focus adjustment must be better than $\lambda/20$.

8-4.5 Reference Path rms Variation. The system must be constructed such that the Reference Path rms Variation shall be less than $\lambda/250$. Measurement of the Reference Path rms Variation is described in para. 8-6.2.1.

8-5 Test Methods

This Section discusses the instrument preparation and measurement procedure for making nanometer surface roughness measurements. Three test methods are described below for measuring the *Rq* of a surface in the nanometer regime.

8-5.1 Instrument Preparations and Environmental Stability. The noncontact phase measuring interferometer system is suitable for nanometer *Rq* measurements when the height resolution (para. E-1.1.2(c) in Nonmandatory Appendix E) is $\frac{1}{10}$ of the *Rq* of the surface being measured. Interferences from the environment such as mechanical vibrations, acoustic (e.g., air flow fans), electrical (e.g., unstable line voltage fluctuations/electromagnetic disturbances), temperature, and humidity variations must be minimized.

8-5.2 Instrument Accuracy. The accuracy of the noncontact phase measuring interferometer is determined by the preciseness of the wavelength of illumination, the vertical digital resolution (number of bits) of the detection of the frames of data, and the amount of shift between frames of measurements.

8-5.2.1 Wavelength. The measurement of the wavelength of illumination may be done by any number of standard spectroscopic techniques. It is appropriate to measure the spectral transmission of the optical passband filter in the system.

8-5.2.2 Phase Shift Adjustment. Techniques for phase shifting adjustment are discussed in (Creath 1988).

8-6 Measurement Procedures

8-6.1 Direct Profile Method. When measuring surfaces of *Rq* on the order of 10 times the Reference Path rms Variation, it is appropriate to take a direct measurement of the profile without correcting for the effects of the reference path. Prior to measurement, the system is brought to optimum focus, the specimen tilt is adjusted to minimize the number of fringes, and the light level is maximized.

8-6.2 Subtract Reference Method. When measuring surfaces of *Rq* between 2 times and 10 times the Reference Path rms Variation, it may be necessary to take a direct measurement of the profile by subtracting the measurement of the reference path profile. The technique for measuring the reference path is described in para. 8-6.2.1. The technique for measuring the test surface profile is described in para. 8-6.1.

8-6.2.1 Measuring the Reference Path Profile and rms Variation. To measure the Reference Path Profile and rms Variation, a super smooth ($Rq < 0.2$ nm) sample free from defects such as digs and scratches must be used. The approximate correlation length for the sample must be known. A number of profile measurements at positions separated by at least the correlation length over the super smooth sample are made. These profile measurements are then averaged together to reduce the roughness effects of the super smooth sample, resulting in the measurement of the Reference Path profile from which the rms Variation is evaluated (Creath 1988).

8-6.3 Absolute *Rq* Method. When measuring samples of *Rq* about 2 times the Reference Path rms Variation or less, it is necessary to eliminate all effects of the reference path. The absolute *Rq* technique involves taking the difference between two measurements of the sample at positions separated by a distance greater than the correlation length. The resulting "difference profile" with rms Variation defined as *Rqd*, has the effects of the reference path removed. The *Rq* of the sample is then estimated from *Rqd* as follows:

$$Rq = Rqd/\sqrt{2} \tag{6}$$

Note that this technique does not produce a profile, but rather a measure of the *Rq* of the specimen.

8-7 Data Analysis and Reporting

The display of the results of a given measurement depends on the procedure that was used to obtain the *Rq* of the surface.

All reports should include the following items:

(a) Wavelength of Measurement.

(b) Specimen *Rq* or other texture parameters per B46.1-2009.

(c) Height resolution, taken prior to the profile measurement.

(d) Measurement of the reference path profile.

(e) Measurement of the Reference Path rms Variation.

(f) Vertical Digital Resolution.

(g) Demonstration of the proper phase shifter adjustment.

(h) Sampling Interval Δ/M and optical spatial resolution $k\lambda/NA$ (choose k as appropriate, typically $k = 0.6$).

(i) For Direct Profile Method. Graph of the surface profile.

(j) For Subtract Reference Method. Graph of the surface profile indicating that the reference path has been subtracted.

(k) For Absolute Rq Method. Indication on the final report that the measurement of *Rq* was performed with the Absolute *Rq* method. Note, no profile should be displayed.

8-8 References

Creath, K, "Phase-Measurement Interferometry Techniques," in *Progress in Optics*, E. Wolf, ed. 26 (1988):349.

Hecht, E., and A. Zajac, *Optics*, (1976), ISBN 0-201-02835-2.

Sanchez Fernandez, L. P., "Interpolation With Splines and FFT in Wave Signals," *Research in Computing Science*, 10 (2004):387–400.

Sanchez Fernandez, L. P., (Spanish language), "Measurement Error of Waves in Research Laboratories," *Hydraulic Engineering in Mexico*, 19 (2) (2004):101–106.

Section 9
Filtering of Surface Profiles

9-1 Scope

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 *Rp*, *Rpm*, and *Rv*, 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 effectively 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 Nonmandatory Appendix G.

9-2 References

The following is a list of standards and specifications referenced in this Standard, showing the year of approval.

ISO 11562-1996 Geometrical Product Specifications (GPS)-Surface texture: Profile method — Metrological characteristics of phase correct filters

ISO 16610-30:2009 Geometrical Product Specifications (GPS)-Filtration — Part 30: Robust Profile Filters: Basic Concepts

Publisher: International Organization for Standardization (ISO), 1 ch. de la Voie-Creuse, Case Postale 56, CH-1211, Genève 20, Switzerland/Suisse (www.iso.org)

See also Sections 1 through 4 of this Standard.

9-3 Definitions and General Specifications

9-3.1 Notes On Terms Defined Previously. This paragraph includes further information on measurement and analysis lengths, as defined in para. 1-3.5, with respect to the surface filtering process.

roughness long-wavelength cutoff, λc: typical 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.), and 8 mm (0.3 in.). The roughness long-wavelength cutoff value used must be clearly specified.

roughness short-wavelength cutoff, λs: typical roughness short-wavelength cutoff values for all types of filters are 0.8 μm (0.00003 in.), 2.5 μm (0.0001 in.), 8 μm (0.0003 in.) and 25 μm (0.001 in.). The roughness short-wavelength cutoff value used must be clearly specified.

traversing length: 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 *λcw*.

waviness long-wavelength cutoff, λcw: form may be separated from waviness on a surface by digital filtering with a Gaussian filter. When this is practiced, a waviness long-wavelength cutoff of the Gaussian filter must be clearly specified. Typical waviness long-wavelength cutoff values for all types of filters are 0.8 mm (0.03 in.), 2.5 mm (0.1 in.), 8 mm (0.3 in.), 25 mm (1 in.), and 80 mm (3 in.).

waviness short-wavelength cutoff, λsw: this value may be equal to the corresponding roughness long-wavelength cutoff ($\lambda sw = \lambda c$), and the filter transmission characteristic may be the complement of the roughness long-wavelength cutoff filter transmission characteristic. Typical waviness short-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.), and 8 mm (0.3 in.). The waviness short-wavelength cutoff value used must be clearly specified.

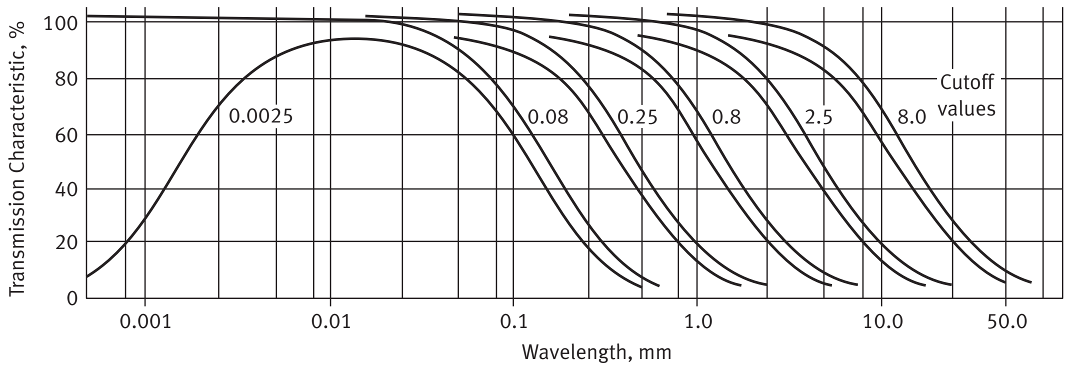
9-3.2 Definitions of Terms Associated With Filtering

cutoff ratio: for roughness or waviness, the ratio of the long-wavelength cutoff to the short-wavelength cutoff.

phase correct profile filters: profile filters which do not cause phase shifts that lead to asymmetric profile distortions.

profile filter: the mechanical, electrical (analog), or digital device or process which is used to separate the

Fig. 9-1 Wavelength Transmission Characteristics for the 2RC Filter System



GENERAL NOTE: The double curve for each cutoff is to address the tolerances associated with a given 2RC filter implementation.

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.

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 Figs. 9-1 and 9-2).

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 λ. The transmission characteristic of a filter is the Fourier transform of the weighting function of the filter.

Each cutoff value (roughness short-wavelength cutoff λs, roughness long-wavelength cutoff λc, waviness short-wavelength cutoff λsw, and waviness long-wavelength cutoff λcw) has a distinct transmission characteristic (see, for example, Figs. 9-4 and 9-5).

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 λs, roughness long-wavelength cutoff λc, waviness short-wavelength cutoff λsw, and waviness long-wavelength cutoff λcw) has an associated weighting function (see Fig. 9-3).

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 (λc) to 2.5 μm (0.0001 in.) or smaller (see Fig. 9-1). Historically, the short-wavelength cutoff generally was determined by the stylus tip radius and other system features. Typically the 2RC system short-wavelength cutoff is limited to 2.5 μm or less. The transmission for a sinusoidal, mechanical input to the stylus shall be flat to within ±7% of unity over the spatial frequency passband region, except in the immediate vicinity of the cutoff wavelength.

9-4.2 Long-Wavelength Cutoff. Typical roughness long-wavelength cutoff values for the 2RC filter are

Fig. 9-2 Gaussian Transmission Characteristics Together With the Uncertain Nominal Transmission Characteristic of a 2 μm Stylus Radius

(Paul Scott, Private Communication), modified

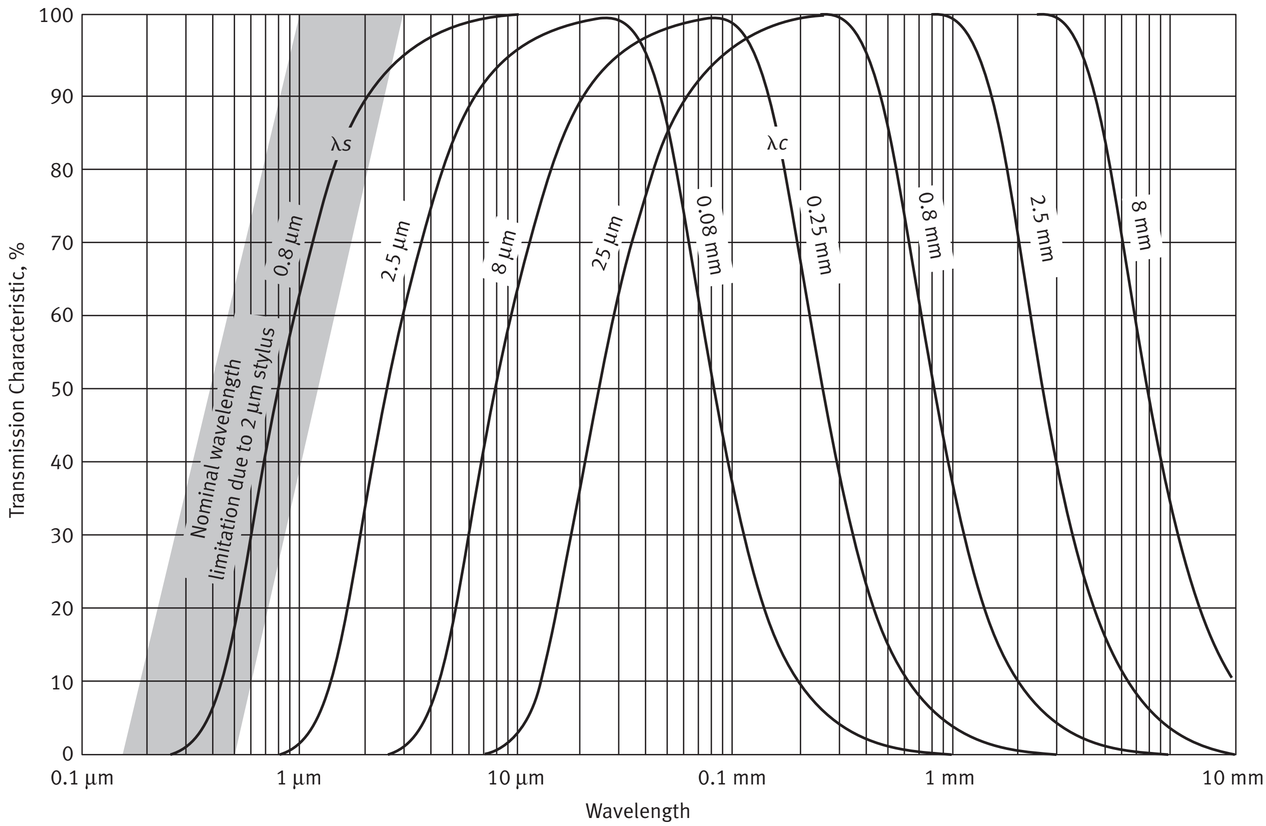
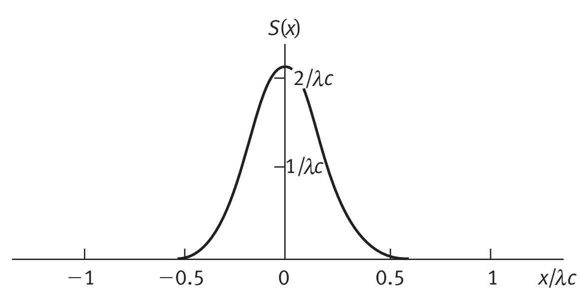


Fig. 9-3 Weighting Function of the Gaussian Profile Filter

(This material is produced from ISO 11562:1996.)



listed in para. 9-3.1. The roughness long-wavelength cutoff λc 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 December 14, 1996. For drawings created or revised earlier, the 0.8 mm value was applied 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 as follows:

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

where the short wavelength roughness cutoff λs is less than or equal to 2.5 μm (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.

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 as follows:

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

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.

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 as follows:

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

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

9-5 Phase Correct Gaussian Filter for Roughness

9-5.1 Phase Correct Gaussian Filter 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, which 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 λc is the spatial wavelength of a sinusoidal profile for which 50% of the amplitude is transmitted by the profile filter. Typical long-wavelength roughness cutoff values are the same for both the Gaussian filter and the 2RC filter and are given in para. 9-3.1. 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 December 14, 1996. For drawings created or revised earlier, the 0.8 mm value was applied, if not specified.

9-5.4 Short-Wavelength Cutoff of the Gaussian Roughness Profile. The cutoff wavelength λs 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

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

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 as follows:

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

where $\alpha = \sqrt{[ln(2)]/\pi} = 0.4697$ and λs is the roughness short-wavelength cutoff. Examples of the transmission characteristic for several values of λs (and also λc) 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 λc, the equation is as follows:

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

In this case, the smoothed profile that results from applying the long-wavelength filter is the roughness mean line, and the roughness profile is found by subtracting this roughness 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:

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

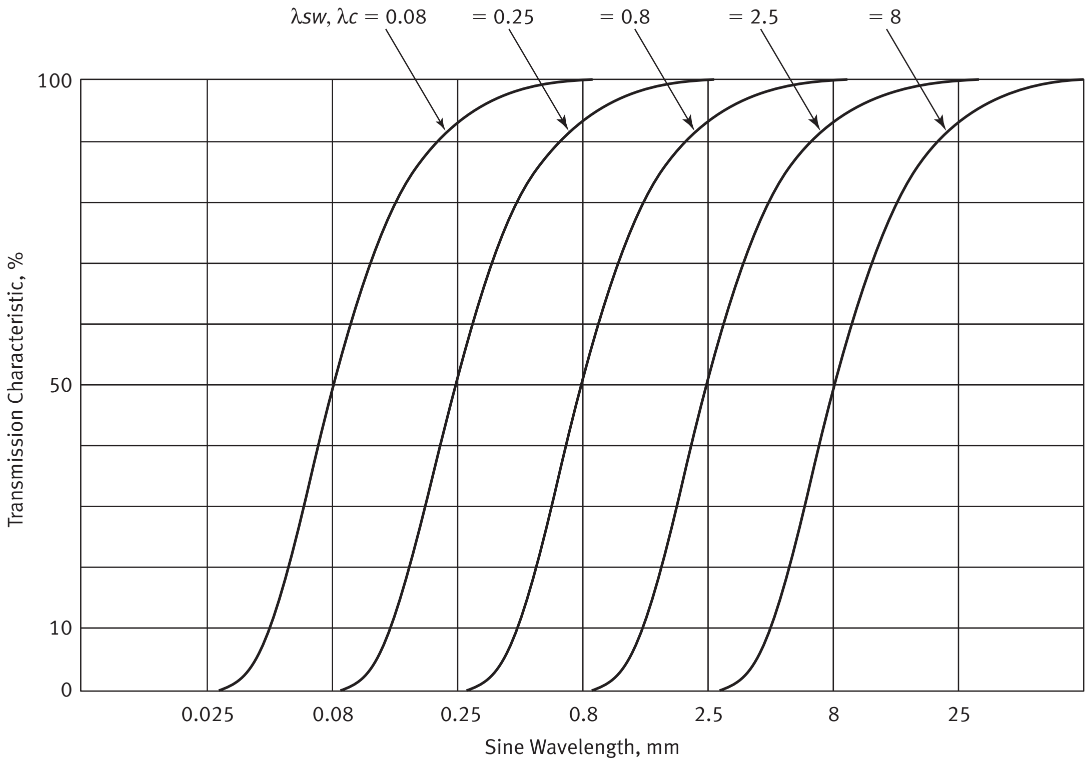
9-5.9 Transmission Characteristic of the Gaussian-Filtered Roughness Profile. The transmission characteristic of the Gaussian filtered roughness profile (see Figs. 9-2 and 9-5) is the complement to the transmission characteristic of the roughness mean line, as defined in para. 9-5.8, because the roughness profile is the difference between the measured profile and the roughness mean line. The equation is therefore given by the following:

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

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

Fig. 9-4 Gaussian Transmission Characteristic for the Waviness Short-Wavelength Cutoff (λsw) or for Deriving the Roughness Mean Line Having Cutoff Wavelengths (λc) of 0.08 mm, 0.25 mm, 0.8 mm, 2.5 mm, and 8.0 mm

(This material is produced from ISO 11562:1996)



graphical representation of the deviations in transmission of the realized digital filter from the Gaussian filter shall be given as a percentage of unity transmission over the wavelength range from 0.01 λc to 100 λc. An example of the deviation curve for an implemented filter 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. Typical values are 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 too large, then some roughness features of interest may be attenuated and not contribute to roughness parameter results. If the short wavelength limit is set too small, then undesirable finely-spaced features may be included in the filtered profile and contribute to parameter results.

9-5.12 Cutoff Ratio. The ratio of the long-wavelength cutoff λc to the short-wavelength cutoff λs of a given transmission band is expressed as $\lambda c/\lambda s$. If not otherwise specified, the values of λs and the cutoff ratio can be obtained from Table 9-2 provided that the long-wavelength cutoff λc is known. The sampling interval (point spacing) should be less than or equal to one-fifth of the short-wavelength cutoff (λs) in order to accurately include all spatial wavelengths that contribute to the filtered profile (see para. 7-4.2.1).

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

Although both the 2RC filter and the Gaussian filter are described here for obtaining the roughness mean line and the roughness profile, only the Gaussian filter is recommended for obtaining the waviness profile by separating waviness from roughness. The transmission characteristic for the roughness mean line is given in

Fig. 9-5 Gaussian Transmission Characteristic for the Roughness Long-Wavelength Cutoff Having Cutoff Wavelengths λc = 0.08 mm, 0.25 mm, 0.8 mm, 2.5 mm, and 8.0 mm

(This material is produced from ISO 11562:1996.)

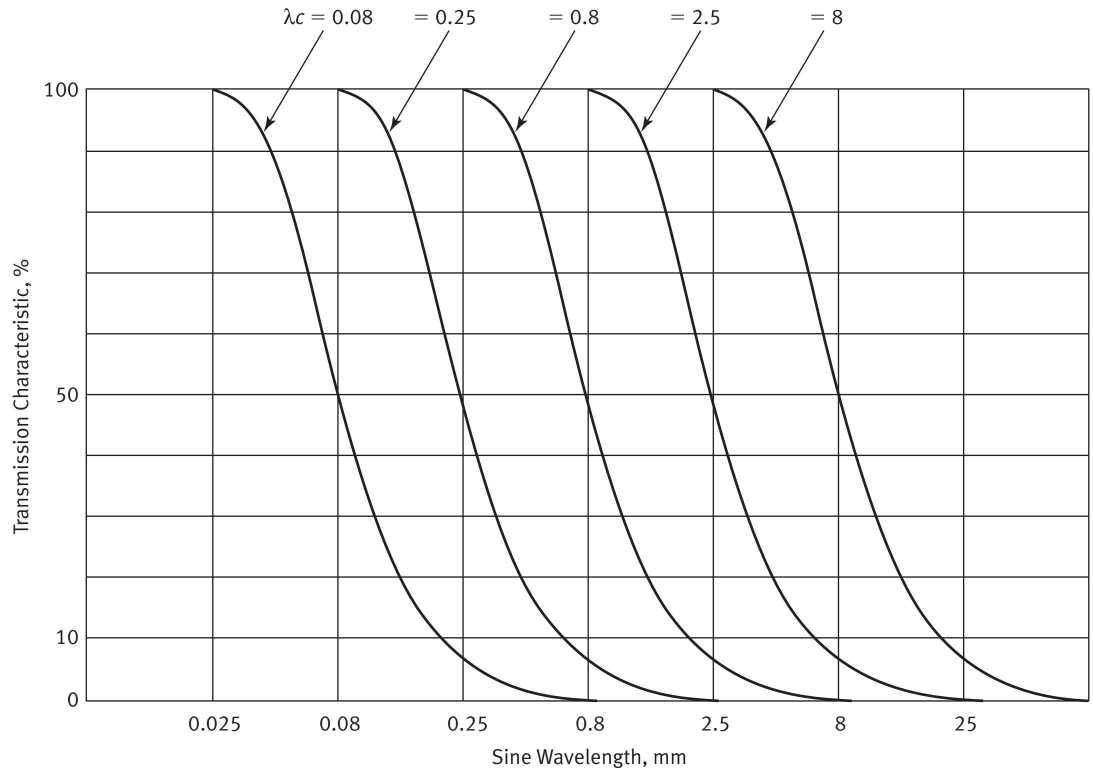


Fig. 9-6 Example of a Deviation Curve of an Implemented Filter From the Ideal Gaussian Filter as a Function of Spatial Wavelength

(This material is produced from ISO 11562:1996.)

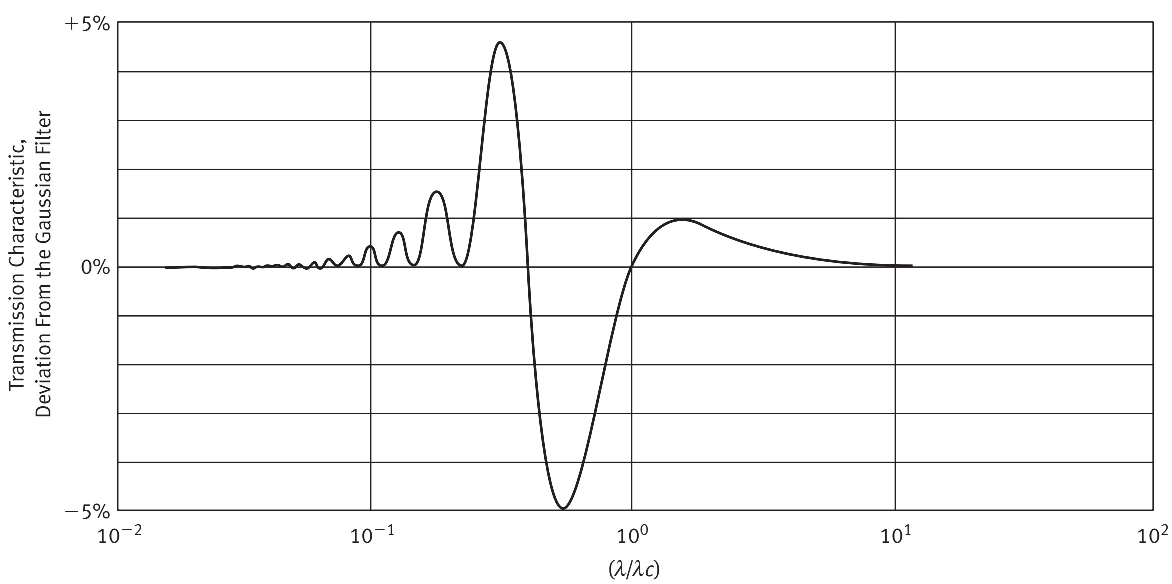


Table 9-2 Typical Cutoffs for Gaussian Filters and Associated Cutoff Ratios

λc, mm (in.)	λs, µm (in.)	$\lambda c/\lambda s$ (Approximate)	r_{tip}, µm (in.)	Max. Sampling Interval, µm (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 (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 µm, the cutoff ratio for λc = 0.08 mm may be set equal to 100:1, provided λs = 0.8 µm and the maximum point spacing = 0.16 µm.

(2) With a nonstandard stylus tip radius of 0.5 µm, the cutoff ratio for λc = 0.25 mm may be set equal to 300:1, provided λs = 0.8 µm and the maximum point spacing = 0.16 µm.

Table 9-3 Typical Values for the Waviness Long-Wavelength Cutoff (λcw) and Recommended Minimum Values for the Waviness Traversing Length

λsw		λcw		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)

para. 9-5.8. The profile representing waviness and form error is therefore 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 λcw to separate form error at the long-wavelength waviness limit. A filtered profile with a waviness long-wavelength cutoff of λcw may be realized by using a Gaussian filter as described below or by least squares methods over profile lengths equal to the waviness cutoff λcw.

9-6.3 Waviness Traversing Length. Typical 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 accomplished in a manner similar to that discussed in para. 9-5.7, by applying a Gaussian filter with a cutoff value equal to the waviness long-wavelength cutoff length λcw in place of λc. The weighting function $S(x)$ for this filter is given by the following 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 Gaussian filters at the short-wavelength cutoff λsw and the long-wavelength cutoff λcw. Typical values for λsw and λcw are given in Table 9-3. A $\lambda cw/\lambda sw$ ratio of 10:1 is implied in Table 9-3, but other ratios may be used.

9-6.5.1 Waviness Short-Wavelength Transmission Characteristic. The waviness 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 para. 9-5.6.

9-6.5.2 Waviness Long-Wavelength 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 λcw limit is given by the following 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.

9-7 Filtering of Surfaces With Stratified Functional Properties

Filtering surfaces which are plateau-like in nature, consisting of deep valley structures, are addressed in the reference in para. 9-2, ISO 16610-30:2009 which, through being referenced in this text, constitutes a provision of this National Standard.

Section 10
Terminology and Procedures for Evaluation of Surface Textures Using Fractal Geometry

10-1 General

10-1.1 Scope. This Section is concerned with terms and procedures for using fractal geometry in the analysis of surfaces. These terms can be used in selecting analysis methods and in reporting the results of fractal analyses. The use of standard terms can facilitate the comparison of analysis methods and promote the understanding of the differences in the results of the different analysis methods.

10-1.2 Limitations. This document recognizes that there are currently several types of fractal analyses in use and that development of fractal analysis methods is continuing. It also recognizes that different types of analyses based on fractal geometry may find applicability in different situations.

10-2 Definitions Relative to Fractal Based Analyses of Surfaces

10-2.1 Basic Terms Relating to Fractal Geometry of Engineering Surfaces

10-2.1.1 Scale of Observation. The size, either linear, or areal at which an observation, analysis or measurement, is made.

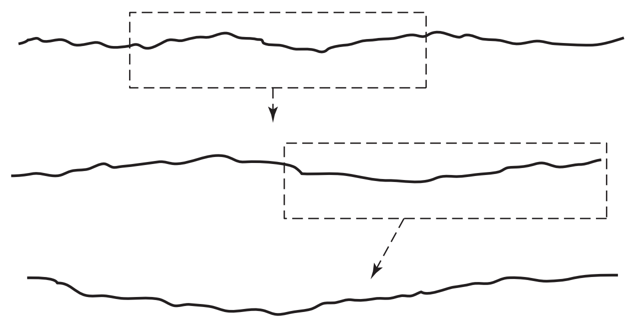
10-2.1.2 Fractal Surfaces. Real surfaces are partially fractal, in that they can be characterized, approximated, or modeled as having irregular, geometric components over some range of scales of observation. Ideal fractal surfaces are mathematical models that have irregular components at all scales of observation.

Periodic and quasi-periodic geometric components of a surface do not exclude that surface from having fractal components or from being advantageously characterized by fractal analysis.

10-2.1.3 Self-Similar. A surface that reveals the same kinds of topographic features that repeat in a statistical sense over a range of scales (Fig. 10-1).

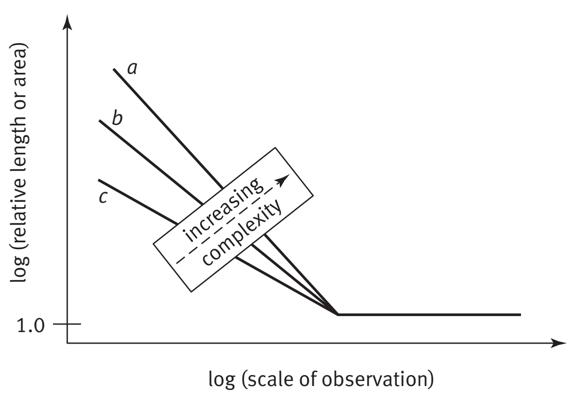
10-2.1.4 Complexity. A measure of the geometric intricacy, or irregularity, as indicated by the change in a geometric property (such as, length or area) with respect to a change in scale of observation (Fig. 10-2). Greater complexities correspond to greater fractal dimensions and steeper slopes on area-scale and length-scale plots (see para. 10-2.2).

Fig. 10-1 Self-Similarity Illustrated on a Simulated Profile



GENERAL NOTE: The regions in the boxes are enlarged to show approximately the same geometric structure on the enlarged region.

Fig. 10-2 An Idealized Log-Log Plot of Relative Length (of a Profile) or Relative Area (of a Surface) Versus the Scale of Observation



GENERAL NOTE: In this case the complexities are in the following order $a > b > c$.

10-2.1.5 Scale-Sensitive Fractal Analysis. Fractal analysis that includes reference to the range of scales over which the fractal dimension(s) apply.

10-2.1.6 Euclidean Dimension. A whole number, equal to the minimum number of coordinates required to locate a point in a space of that dimension. To locate a point on a line requires only one coordinate, the distance along the line, hence the dimension of the line is one; to locate a point on a plane requires two coordinates, hence the dimension is two.

10-2.1.7 Fractal Dimension (*D*).[1] The ratio of the log of the number of linear or areal elements N with respect to the log of the reciprocal of the linear scaling ratio r.

$$D = (\log N)/[(\log (l/r)] \tag{1}$$

A linear element is a line segment, or step length. An areal element is a tile, or patch. The linear scaling ratio is any fraction of the nominal profile (para. 1-3.1). The scaling ratio times the length of a nominal profile is the linear scale of observation.

All methods for determining a fractal dimension should be consistent with the above expression. Each method for determining the fractal dimension shall include a qualifier indicating the method.

For an ideal fractal surface, eq. (1) represents the slope of a log-log, length-scale or area-scale plot because all scales are covered, including, $r = 1$ (at which point $N = 1$ as well). For real surfaces this will not be true in general. On real surfaces the fractal dimensions are calculated from the slope of these plots in a scale range over which the surface is self similar.

The fractal dimension is a measure of the geometric complexity, or intricacy of a fractal or partially fractal surface. The fractal dimension increases with increasing complexity. The fractal dimension is greater than or equal to the Euclidean dimension (i.e., greater than or equal to one and less than two for a profile, and greater than or equal to two and less than three for a surface).

10-2.1.7.1 Length-Scale Fractal Dimension (Dls). The fractal dimension derived from the slope of a log-log plot of relative length versus scale of observation (see para. 10-2.2.1).

$$\text{Dls} = 1 - \text{slope}$$

10-2.1.7.2 Area-Scale Fractal Dimension (Das). The fractal dimension derived from a log-log plot of relative area versus scale of observation (see para. 10-2.2.2).

$$\text{Das} = 2 - 2\ (\text{slope})$$

[1] B.B. Mandelbrot, Fractals Form Chance and Dimension, W.H. Freeman and Company, San Francisco 1977.

10-2.1.8 Complexity Parameter. A parameter that can be derived from the fractal dimension, and which preserves the ranking of surfaces achieved with the fractal dimension.

Since many surfaces of engineering interest have small fractal dimensions (i.e., fractal dimensions a few hundredths or thousandths above the Euclidean dimension), the use of a complexity parameter in place of the fractal dimension can be a matter of convenience.

10-2.1.8.1 Length-Scale Fractal Complexity (Lsfc). A complexity parameter derived from length-scale analysis, equal to −1000 times the slope of a log-log plot of relative length versus scale of observation, or Lsfc = 1000 (Dls − 1). See para. 10-2.2.1.

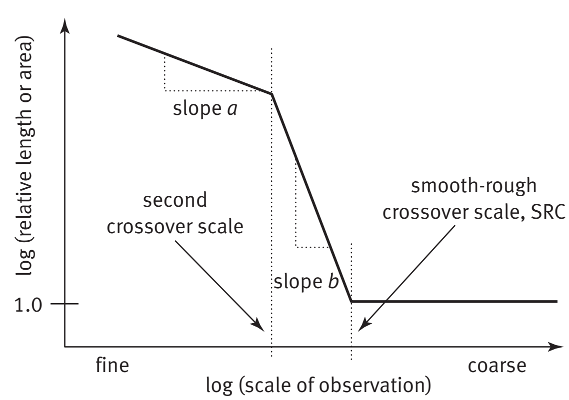
10-2.1.8.2 Area-Scale Fractal Complexity (Asfc). A complexity parameter derived from area-scale analysis, equal to −1000 times the slope of a log-log plot of relative area (of a surface) versus scale of observation, or Asfc = 1000 (Das − 2). See para. 10-2.2.2.

10-2.1.9 Multi-Fractal Surface. A surface whose complexity, and hence fractal dimension, changes as a function of scale of observation (Fig. 10-3).

10-2.1.10 Crossover Scale. The scale of observation at which there is a change in the fractal dimension (Figs. 10-3 and 10-6). Since the change in fractal dimension is not necessarily abrupt with respect to scale, a procedure is necessary for determining the scale at which the change takes place.

10-2.1.11 Smooth-Rough Crossover Scale (SRC). The first crossover scale encountered going from relatively larger scales, where the surface appears to be

Fig. 10-3 An Idealized Log-Log Plot of Relative Length or Area Versus the Scale of Observation (Length-Scale or Area-Scale Plot), Showing Multi-Fractal Characteristics and Crossover Scales



GENERAL NOTE: The crossover scales are scales where there is a change in slope, indicating a change in fractal dimension. In this case the second crossover scale indicates a change to a lower complexity at finer scales (−slope *a* < −slope *b*).

smooth, to finer scales where the surface appears to be rough.

The SRC is the scale above which the fractal dimension is approximately equal to the Euclidean dimension, and below which it is significantly greater than the Euclidean dimension. A threshold in relative length or relative area is used to determine the SRC in length-scale and area-scale analyses (Figs. 10-3 and 10-6).

10-2.1.11.1 Threshold (*Th*). The value of the relative length (see para. 10-2.2.1) or relative area (see para. 10-2.2.2) used to determine the smooth-rough crossover scale (Fig. 10-6). Starting from the largest scales, working towards the smallest, the first relative length or relative area to exceed the threshold is used to determine the *SRC*.

A value of relative length or area can be specified for the threshold, or the threshold can be selected as some fraction P of the largest relative length or area in the analysis in the following manner:

$Th = 1 + (P)$ (maximum relative area or length − 1)

The value of P shall be 0.1, unless otherwise noted.

10-2.2 Analysis Methods and Associated Terms

10-2.2.1 Length-Scale Analysis. Also known as compass, coastline, or Richardson analysis. The apparent lengths of a profile measured as a function of the scales of observation by a series of stepping exercises along the profile, as with a compass or dividers. The length of the step, or separation of the compass or dividers, represents the linear scales of observation. The stepping exercises are repeated with progressively shorter steps to determine the measured lengths as a function of the linear scales of observation (Fig. 10-4).

10-2.2.1.1 Measured Length. The number of steps times the step length (i.e., scale of observation) for one stepping exercise along the profile. The measured length is the apparent length of the profile at a particular scale of observation and must be referenced to that scale as the measured length at a particular scale. For example, the measured length is 160 μm at a scale of 10 μm, for one of the examples in Fig. 10-4.

10-2.2.1.2 Nominal Length. The length of the nominal profile (para. 1-3.1) (i.e., the straightline distance along the nominal profile from the starting point to the end point of a stepping exercise). The least squares mean line (para. 1-3.2), or the measurement datum can be used for the nominal profile.

10-2.2.1.3 Relative Length. The measured length for a stepping exercise at a particular scale of observation divided by the nominal length of the profile covered by the stepping exercise. Consequently the minimum relative length is one.

10-2.2.1.4 Length-Scale Plot. A log-log plot of the relative lengths versus the linear scales of observation.

10-2.2.2 Area-Scale Analysis. The apparent area of a measured surface is calculated as a function of scale by a series of virtual tiling exercises covering the measured surface in a patchwork fashion. The areas of the tiles or patches represent the areal scales of observation. The tiling exercises are repeated with tiles of progressively smaller areas to determine the measured areas as a function of the areal scales of observation (Fig. 10-5).

10-2.2.2.1 Measured Area. The number of tiles, or patches, for one virtual tiling exercise times the area of the tile, or patch (i.e., scale of observation). The measured area is the apparent area at a particular scale of observation and must be referenced to that scale, as the measured area at a particular scale. For example, the measured area is 18,331 tiles × 7,830 nm^2 = 143,531,730 nm^2 at a scale of 7,830 nm^2.

10-2.2.2.2 Nominal Area. The area of an individual tiling exercise projected onto the nominal surface (para. 1-2.1) (i.e., the area on the nominal surface covered by the tiling exercise). The least squares plane, or the measurement datum can be used for the nominal surface.

10-2.2.2.3 Relative Area. The apparent measured area for a tiling exercise at a particular scale of observation divided by the nominal area covered by that tiling exercise. Consequently the minimum relative area is one.

10-2.2.2.4 Area-Scale Plot. A log-log plot of the relative areas versus the areal scales of observation (Fig. 10-6).

10-3 Reporting the Results of Fractal Analyses

The report of the results of fractal analysis can be in either one or both of two parts as follows:

(a) Part 1. A plot of the log of a geometric property (e.g., relative length or area) of the measured profile or surface versus the log of the scale of measurement (e.g., step length or tile area). See example in Fig. 10-6.

(b) Part 2. A characterization of the plot of the geometric property versus scale. See example in Table 10-1.

10-3.1 Limits on the Scales of Observation. The report shall not include any observations outside the limits on the scales of observation, unless noted, except where the resolution of the instrument is unknown; then the sampling interval shall be used to determine the minimum scale of observation.

10-3.1.1 Measured Profiles. The smallest possible linear scale of observation is either the sampling interval (para. 1-3.4), or the spatial resolution, whichever is larger. The largest linear scale of observation is the evaluation length (para. 1-3.4).

10-3.1.2 Measured Surfaces. The smallest possible areal scale of observation is 0.5 times the product of

Fig. 10-4 Three Stepping Exercises From a Length-Scale Analysis on a Simulated Profile

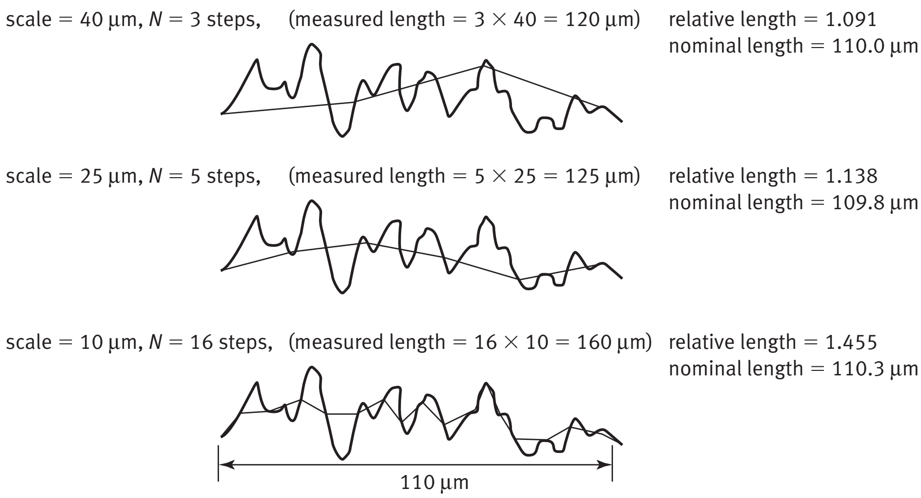
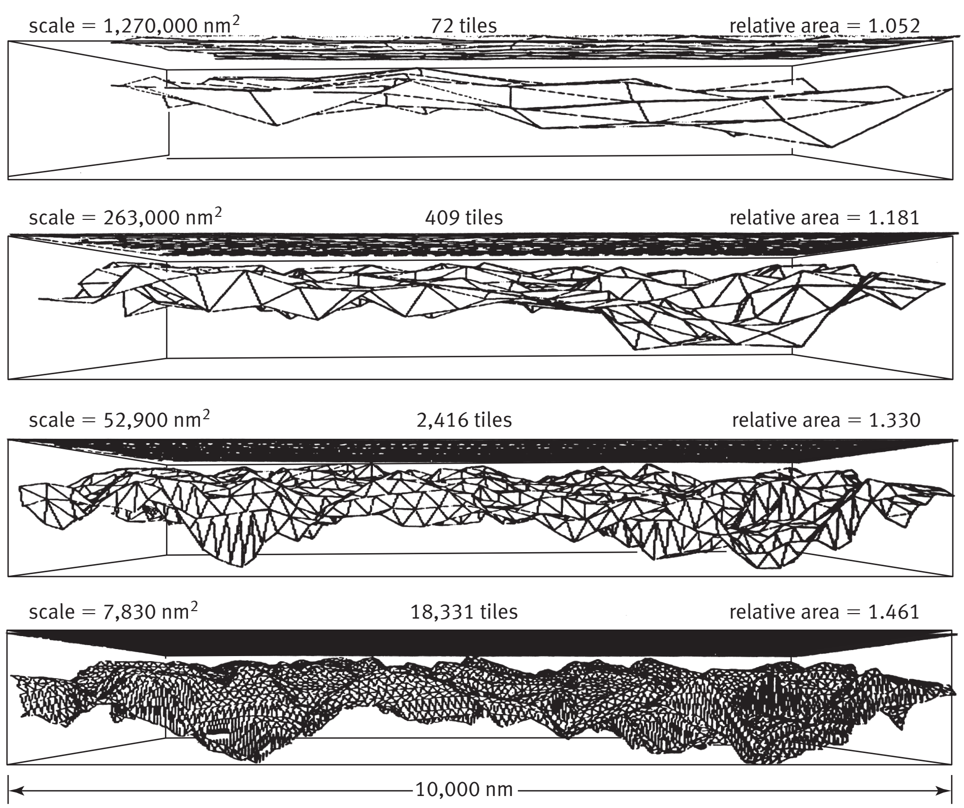
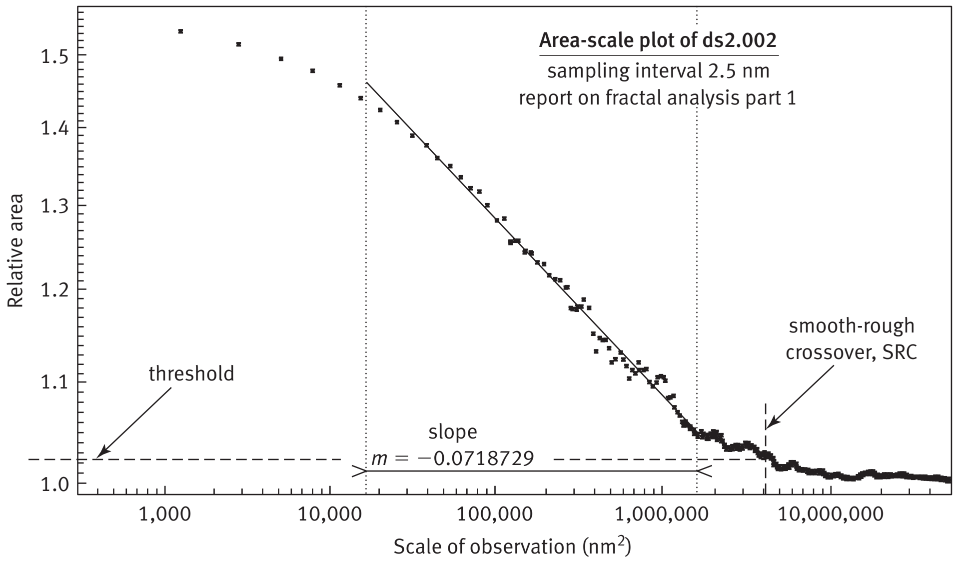


Fig. 10-5 Four Tiling Exercises From an Area-Scale Analysis



GENERAL NOTE: The triangluar tiles, or patches, are shown in outline. The total area measured by the tiles increases as the scale of observation (tile area) decreases. The nominal areas covered by each tiling exercise are represented on the ceiling of each box. The measured area can be calculated as the scale times the number of tiles. Note that there is some distortion of the tiles in the display. In each tiling exercise the tiles all have the same area, which is the scale.

Fig. 10-6 An Area-Scale Plot Including the Results of the Tiling Series in Fig. 10-5



GENERAL NOTE: The smooth-rough crossover is about $3x10^6$ nm^2, for a threshold in relative area of 1.02. The area-scale fractal complexity, Asfc = −1000 (slope), is about 71.87 and the area-scale fractal dimension, Das = 2 − 2 (slope), is about 2.144. This plot also serves as an example of a standard report of a geometric property versus scale, in which the comments in italics are optional.

Table 10-1 Example of a Report on Fractal Analysis

Report on Fractal Analysis of a Measured Surface, Part 2		
Measured surface: ds2.002		
Sampling interval: 2.5 nm		
Measuring instrument: Nanscope II, STM		
Complexity:		
Asfc = 71.87	Scale range: 15,600 to 1,560,000 nm^2	R^2 = 0.989
Das = 2.144	same as above	
Slope = −0.07187	same as above	
Smooth-rough crossover:		
SRC = 3,000,100 nm^2	Threshold in relative area: 1.02	

the sampling intervals in x and y (assuming a triangular tile), or the minimum resolvable area. The largest areal scale of observation is the evaluation area (see para. 1-5.4).

10-3.2 Plot of a Geometric Property Versus Scale. For any plot the following information is required: the plot, with the geometric property on the vertical axis and the scale of observation on the horizontal axis, and the points on the plot must represent the individual results of geometric property calculations as a function of the scale of observation. The units shall be indicated where appropriate. Geometric properties like relative length and relative area are unitless.

The geometric properties can be evaluated at scales separated by logarithmic or linear intervals.

For any plot other than those described above, the method by which the plot was generated shall be reported.

10-3.3 Complexity Parameter. For any method of calculating the complexity, the range of scales of observation over which the complexity parameter applies and the regression coefficient, R^2 (for example from regression analysis of a portion of a length-scale or area-scale plot), to indicate how well it applies over this range, shall be reported.

10-3.3.1 Supporting Information. The method for calculating the complexity parameter from the plot of a geometric property versus scale, its relation to the fractal dimension, and the method for generating the plot from which it was calculated, shall be reported in detail, unless the method is described in the above paragraphs (i.e., paras. 10-2.1.8.1 and 10-2.1.8.2) and these paragraphs are referenced.

10-3.4 Fractal Dimension. For any method of calculating the fractal dimension, the range of scales of observation over which the fractal dimension applies and the regression coefficient, R^2 (for example from regression analysis of a portion of a length-scale or area-scale plot), to indicate how well it applies over this range, shall be reported.

10-3.4.1 Supporting Information. The method for calculating the fractal dimension from the plot of a geometric property versus scale, the method for generating the plot and the scale range over which the fractal dimension was calculated shall be reported in detail, unless the method is described in the above paragraphs (i.e., paras. 10-2.1.7.1 and 10-2.1.7.2) and these paragraphs are referenced.

10-3.5 Slope of Plots of Geometric Property versus Scale. For any plot other than those described above (length-scale and area-scale), the method by which the plot was generated is required as supporting information. The line used for determining the slope is generated by a least squares regression analysis, unless otherwise noted. Regression analyses are not required for plots, only for the determination of parameters.

10-3.5.1 Supporting Information. The scale range over which the least squares regression has been determined, the regression coefficient, R^2 (for all regression analyses), and the number of points used in the regression analysis.

10-3.6 Smooth-Rough Crossovers (SRC). The following supporting information is required for other than length-scale and area-scale analyses: the method for determining the SRC and the values of any threshold parameters, possibly as a percentage of some quantity.

The following supporting information is required for length-scale and area-scale analyses: the value of the threshold in relative length or relative area that has been used to determine the SRC, possibly as a percentage of the maximum relative length or area (see para. 10-2.1.11.1).

The units on SRC shall be the same as the units of the horizontal axis of the plot.

The reporting of the SRC implies that at some sufficiently large scale, which has been measured, the surface is sufficiently smooth to be considered Euclidean.

10-4 References

The following references are for information only:

Briones, V., C.A. Brown, and J.M. Aguilera, "Scale-sensitive Fractal Analysis of the Surface Roughness of Bloomed Chocolate," *Journal of American Oil Chemists Society*, 83 (3) (2006):193–199.

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Stemp, W.J., B.E. Childs, S. Vionnet, and C.A. Brown, "Quantification and Discrimination of Lithic Use-Wear: Surface Profile Measurements and Length-Scale Fractal Analysis," *Archaeometry*, in press (2008).

Section 11
Specifications and Procedures for Precision Reference Specimens

11-1 Scope

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

Much of the technical information, including tables, has been adapted from ISO 5436-1:2000.

ISO 5436-1:2000, Surface Texture: Profile Method; Measurement Standards — Part 1: Material Measures
Publisher: International Organization for Standardization (ISO), 1 ch. de la Voie-Creuse, Case Postale 56, CH-1211, Genève 20, Switzerland/Suisse (www.iso.org)

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.

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 (A, B, C, and D) are described in paras. 11-4.1 through 11-4.4, 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.

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

Fig. 11-1 Type A1 Groove

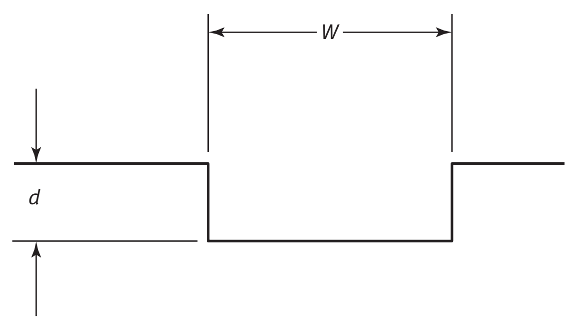


Fig. 11-2 Type A2 Groove

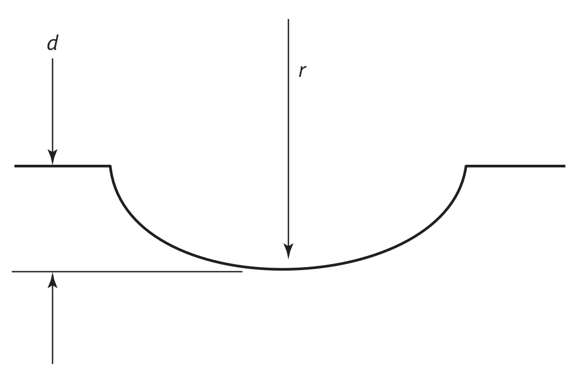
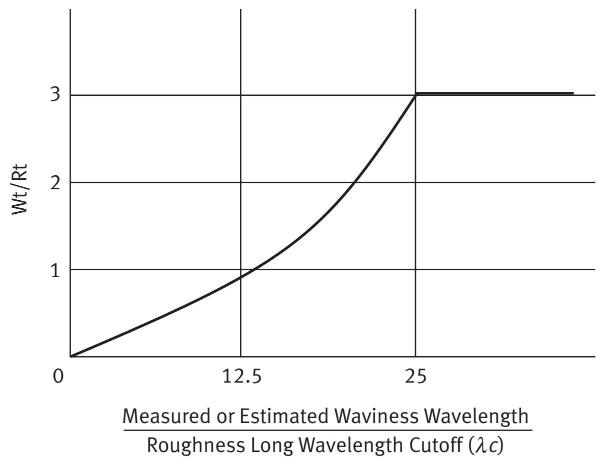


Fig. 11-3 Allowable Waviness Height *Wt* for Roughness Calibration Specimens



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 peak 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 stable enough to ensure adequate life and be consistent with the type of instrument being used; for example, hard materials for contacting instruments and optically uniform materials for optical instruments.

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 and Flatness Limits. For roughness specimens, the waviness, measured with respect to a flat datum, shall have waviness height, *Wt*, no greater than the values shown in Fig. 11-3. Step height specimens shall have peak-to-valley flatness over the local surface area to be measured that is less than 2 nm or 1% of the step height being examined, whichever is greater.

11-6 Assigned Value Calculation

Each precision reference specimen shall have an assigned value clearly marked near the designated measuring area of the specimen. The assigned value shall be the mean of composite values from at least nine uniformly distributed locations on the designated measuring area as follows:

$$\text{Assigned Value} = \sum_{i=1}^{n} V_i/n$$

where n is greater than or equal to 9, and where the composite value V_i of each location shall consist of the mean of at least two individual readings of the measured parameter being assigned. For example,

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

where $i = 1, 2, \ldots$, n, and R_{i1} or R_{i2} is the measured value of the parameter calculated from a single measurement.

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.

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 (*C*) 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 levelled so that its measured surface is 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

Fig. 11-4 Assessment of Calibrated Values for Type A1

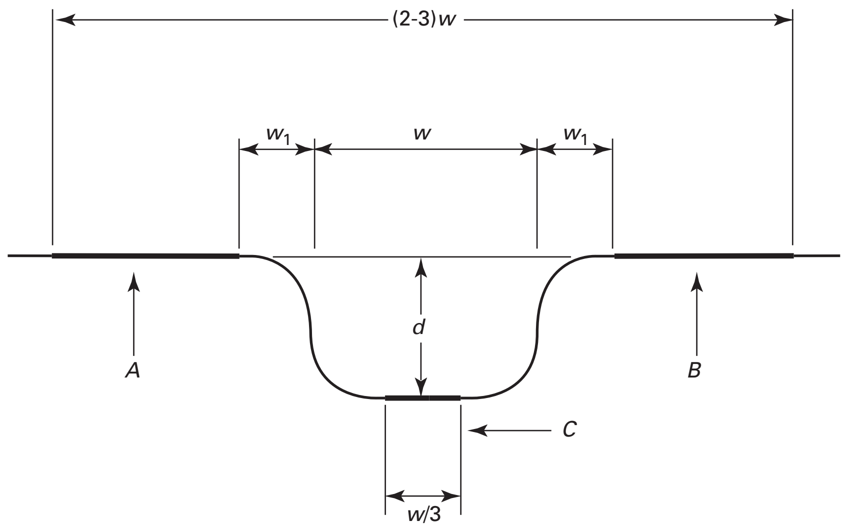


Table 11-2 Nominal Values of Depth and Radius for Type A2

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 and Uncertainties for Types A1 and A2

Nominal Value of Depth or Height, μm	Tolerance on Nominal Value, %	Combined Expanded Uncertainty of Measurement in Calibrated Mean Value of Depth or Height, % [Notes (1), (2)]	Uniformity — One Standard Deviation From the Calibrated Mean, %
0.3	±20	±4	±3
1	±15	±3	±2
3	±10	±3	±2
10	±10	±3	±2
30	±10	±3	±2
100	±10	±3	±2

NOTES:
(1) Assumed in this document to be at the two standard deviations (or approximately 95% confidence) level (see para. 7-2).
(2) Taken from at least nine uniformly distributed measurements (see para. 11-6).

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 typically 20 μm, 10 μm, 5 μm, and 2.5 μm (see Fig. 11-5). The size and condition of the stylus is estimated from the profile graphs (see Table 11-4). The bottom of the grooves is not a functional feature of the specimen. Therefore, the grooves should be sufficiently deep such that the stylus tip does not touch the bottom. For example, the depth of the grooves should be greater than one-half of the width of the widest groove for a stylus with a 90-deg included angle. For styli with other included angles, an appropriate groove depth must be used.

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

For testing 10 μm radius tips, a useful B2 specimen design has $\alpha = 150$ deg and an *ideal Ra* of 0.5 μm ±5% (i.e., measured with a stylus with radius much finer than 10 μm). The mean peak spacing *RSm* 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 shall remain 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, for example, 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

Fig. 11-5 Type B1 Grooves: Set of Four Grooves

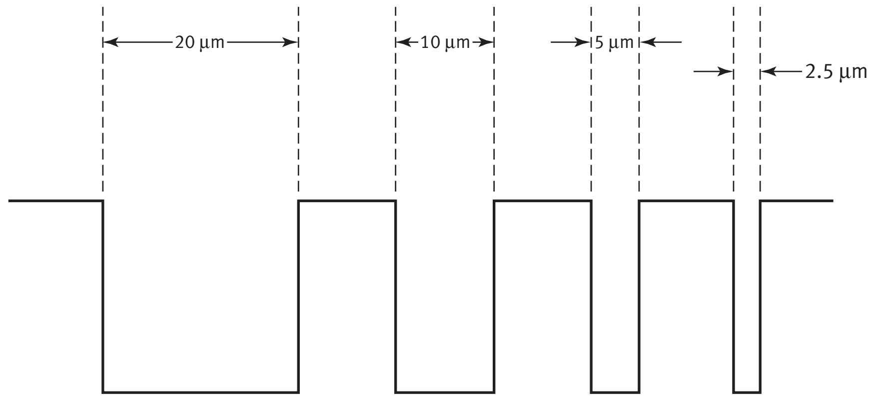
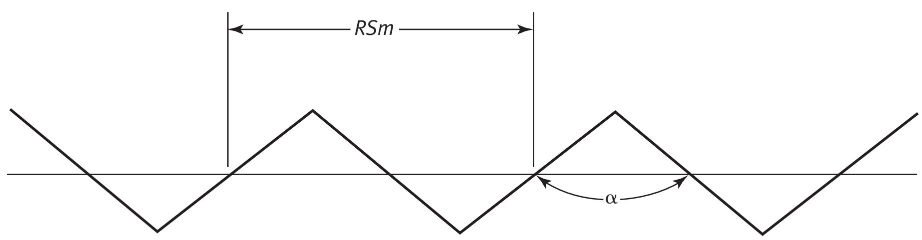


Table 11-4 Tip Size Estimation From the Profile Graph for Type B1

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

GENERAL NOTE: Assuming the tip has a standard 90-deg included angle.

Fig. 11-6 Type B2 or C2 Specimens With Multiple Grooves



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

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

(b) Type C2. Grooves having an isosceles triangle profile (see Fig. 11-6). See Table 11-7 for nominal values of *Ra* and *RSm*. For tolerances and uncertainties, see Table 11-6.

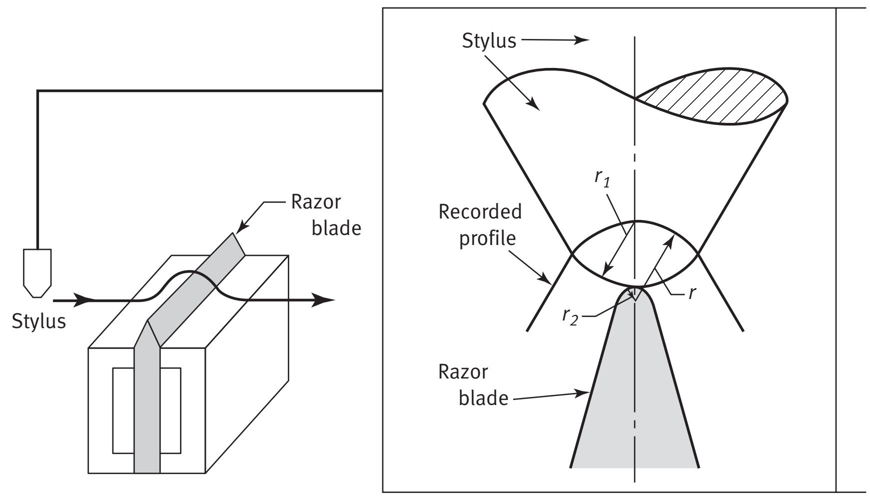
(c) Type C3. Simulated sine wave grooves include triangular profiles with rounded or truncated peaks and valleys (see Fig. 11-9), the total rms harmonic content of which shall not exceed 10% of the rms value of the fundamental. Recommended values of *Ra* and *RSm* are the same as those shown for Type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

(d) Type C4. Grooves having an arcuate profile (see Fig. 11-10). For recommended values of *Ra* and *RSm*, see Table 11-8. For tolerances and uncertainties, see Table 11-6.

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.

11-7.4 Type D1 and D2. These specimens have an irregular profile which is repeated at length intervals equal to $5\lambda c$ along the direction that is perpendicular to the lay of a specimen with unidirectional lay (Type D1) or radial direction of a specimen with circumferential lay (Type D2) (see ISO 5436-1:2000). The grooves on the

Fig. 11-7 Use of Type B3 Specimen



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 included 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. 11-8 Type C1 Grooves

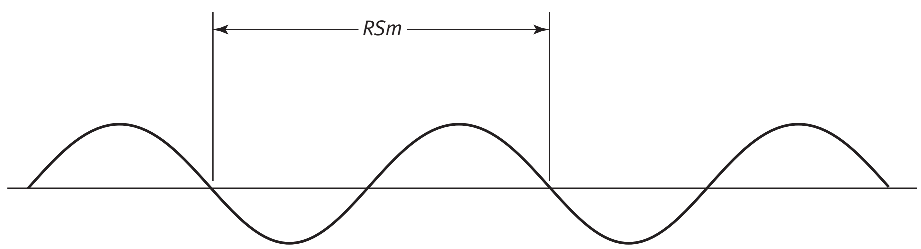


Table 11-5 Typical *Ra* and *RSm* Values for Type C1

Mean Spacing of Profile Irregularities *RSm*, mm	Selected Cutoffs (mm) to Check *Ra*		*Ra*, μm	
0.01	0.08	. . .	0.1	0.3
0.03	0.25	0.1	0.3	1
0.1	0.8	0.3	1	3
0.3	2.5	1	3	10

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

Table 11-6 Tolerances and Uncertainties for Types C1 Through C4

Nominal Value of *Ra*, μm	Tolerance on Nominal Value, %	Combined Expanded Uncertainty of Measurement in Calibrated Mean Value of *Ra*, % [Notes (1), (2)]	Standard Deviation From Mean Value, %
0.1	±25	±4	±3
0.3	±20	±3	±2
1	±15	±3	±2
3	±10	±2	±2
10	±10	±2	±2

NOTES:
(1) Assumed in this document to be at the two standard deviations (or approximately 95% confidence) level (see para. 7-2).
(2) Taken from at least nine uniformly distributed measurements (see para. 11-6).

Table 11-7 Typical Values of *Ra* and *RSm* for Type C2

Mean Spacing of Profile Irregularities, *RSm*, mm					
0.06	**0.1**	**0.25**	**0.8**	**2.5**	
		***Ra*, μm**			**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

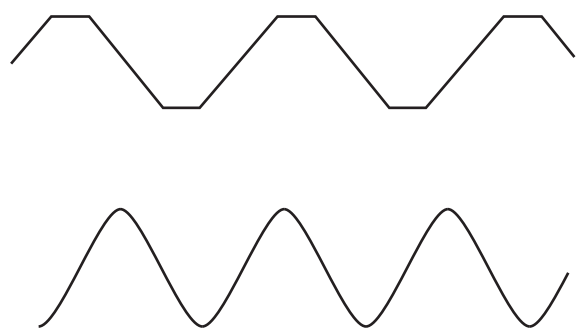


Fig. 11-10 Type C4 Grooves

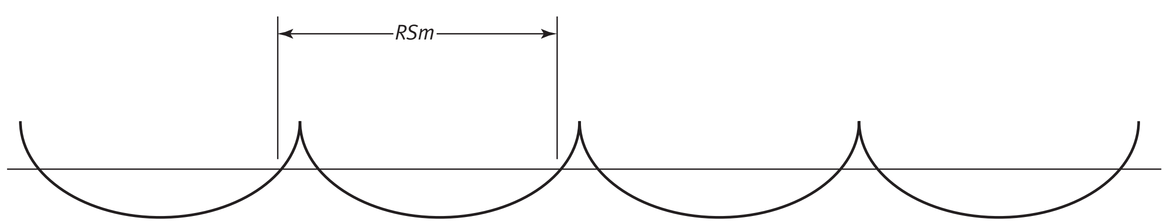


Table 11-8 Typical Values of *Ra* for Type C4

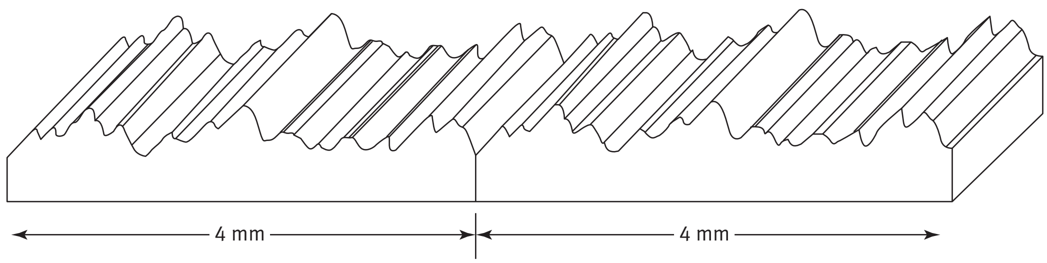
Mean Spacing of Profile Irregularities, *RSm*, mm [Note (1)]	*Ra*, μm			
0.25	0.2	3.2	6.3	12.5
0.8	3.2	6.3	12.5	25.0

GENERAL NOTE: Neglecting any attenuation by the filter.

NOTE:

(1) The filter cutoff λc must be at least 5 times larger than the *RSm* values shown here.

Fig. 11-11 Unidirectional Irregular Groove Specimen Having Profile Repetition at $5\lambda c$ Intervals (Type D1 With $\lambda c = 0.8$ mm)



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 *Ra* values of the specimens may range from 0.01 μm to 1.5 μm. For tolerances of certain higher *Ra* values in this range, see Table 11-9. Recommended tolerances for the smaller *Ra* 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

(2) for Type B2, the estimated mean *Ra* value for a probe tip of specified radius

(3) for Types C and D, the calibrated mean value of *Ra* 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 11-9 Tolerances and Uncertainties for Types D1 and D2

Nominal Value of *Ra*, μm	Tolerance on Nominal Value, %	Combined Expanded Uncertainty of Measurement in Calibrated Mean Value of *Ra*, % [Notes (1), (2)]	Standard Deviation From Mean Value, %
0.15	±30	±5	±4
0.5	±20	±4	±3
1.5	±15	±4	±3

GENERAL NOTE: These values correspond to Types D1 and D2 specimens with profile repetition length intervals ($5\lambda c$) equal to 4 mm (λc = 0.8 mm).

NOTES:

(1) Assumed in this document to be at the two standard deviations (or approximately 95% confidence) level (see para. 7-2).

(2) Taken from at least 12 uniformly distributed measurements (see para. 11-6).

11-9 Calibration Interval

Reference specimens should be calibrated on a regular basis,[1] as documented in the end user's quality system. Possible considerations for determining the calibration interval may include the amount of use, wear, environment, instrument type (contact, noncontact), required accuracy, and application.

[1] ISO/IEC 17025:2005.

Section 12
Specifications and Procedures for Roughness Comparison Specimens

12-1 Scope

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 also discussed in para. B-3, Nonmandatory Appendix B.

12-2 References

The following is a list of publications referenced in this Standard.

ISO 2632-1:1985, Roughness Comparison Specimens — Part 1: Turned, Ground, Bored, Milled, Shaped and Planed

Publisher: International Organization for Standardization (ISO), 1 ch. de la Voie-Creuse, Case Postale 56, CH-1211, Genève 20, Switzerland/Suisse (www.iso.org)

See Sections 1, 2, and 6 of this Standard.

12-3 Definitions

roughness comparison specimen: a specimen that has a 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 (see para. 12-9). 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.

Table 12-1 Nominal Roughness Grades (*Ra*) 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

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 (*Ra*) grades for various manufacturing processes are listed in Table 12-3 along with corresponding sampling lengths.

12-7 Specimen Size, Form, and Lay

Comparison specimens must be of adequate size and consistent with Table 3-1 to permit initial calibration

Table 12-2 Form and Lay of Roughness Comparison Specimens Representing Various Types of Machined Surfaces

Process Represented	Form of Specimen	Lay
Peripheral O.D. grinding	Convex cylindrical	Uniaxial
I.D. grinding	Concave cylindrical	Uniaxial
Peripheral flat grinding	Flat	Uniaxial
Side-Wheel grinding	Flat	Crossed arcuate
Cup-Wheel grinding	Flat	Crossed arcuate
O.D. turning	Convex cylindrical	Uniaxial
I.D. 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

and periodic verification. For specimen surfaces having nominal *Ra* values of 6.3 μm or less, no side should be less than 20 mm. For the *Ra* value 12.5 μm, no side should be less than 30 mm. For *Ra* values greater than 12.5 μm, 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 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 nominal and measured values of the assigned parameter(s) (conventionally *Ra*) and the unit of measurement (e.g., μm)

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

(c) the designation, *comparison specimen*

Table 12-3 Examples of Sampling Lengths for Calibration of Comparison Specimens, mm

	Nominal *Ra*, μm																
Type of Surface	**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**
Machine 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.

NONMANDATORY APPENDIX A
GENERAL NOTES ON USE AND INTERPRETATION OF DATA PRODUCED BY STYLUS INSTRUMENTS

A-1 INTRODUCTION

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.

A-2 ROUGHNESS AVERAGE

One useful quantity in characterizing a surface is the roughness average *Ra*, 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 *Ra* that are in reasonable agreement on any given surface.

A-3 STYLUS TIP RADIUS

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 from 2 μm to 10 μm 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.

A-4 SKIDDED MEASUREMENTS

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.

A-5 TRAVERSING LENGTH AND MEASUREMENT STATISTICS

Since most surfaces are not uniform, 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. For certain machining processes, it is possible to obtain adequate surface finish control with three measurements. If the process used produces parts that vary widely in roughness average *Ra* 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.

A-6 FILTER CUTOFF SELECTION

In general, surfaces contain profile features characterized by a large range of spatial wavelengths (i.e., lateral peak spacings). Some instruments are designed to respond only to lateral peak spacings less than a given value, called the roughness long-wavelength cutoff (λc). Such instruments can be configured to include long-wavelength features within the filtered roughness profile and its associated roughness parameters by setting the filter cutoff to a larger value. With the advent of dual band-pass filtering techniques (roughness and waviness), instruments that have this capability are now able to measure long-wavelength features separately as waviness. This current practice is described in more detail in ASME B46.1 Sections 3, 9, and Nonmandatory Appendix G. Examples of surfaces including important long-wavelength features are milled surfaces having an undulating profile (i.e., waviness) in addition to finely-spaced roughness features, and machined surfaces exhibiting chatter marks (e.g., shaft surfaces).

A-7 METHODS FOR ROUGHNESS AND WAVINESS SEPARATION

Methods for separating roughness and waviness aspects of the surface (segmentation,[1] 2RC filtering, and Gaussian filtering) are discussed in ASME B46.1. These methods may produce different measured parameter values. The numerical difference between these values is referred to as *methods divergence*. The methods divergence arises here because the methods produce different mean lines and yield different attenuation rates for profile spatial wavelengths near the cutoff or roughness sampling length. The filtered mean line for instruments using either a 2RC or Gaussian filter is a wavy one, generally following the shape of the larger irregularities of the profile. In the segmentation procedure, the mean line is composed of straight line segments, each having a length equal to the roughness sampling length. The transmission characteristics of the Gaussian filter 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 25%. In the segmentation procedure, less than 25% 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. In cases of disagreement regarding the interpretation of measurements, see para. 2-2 of ASME B46.1.

[1] This technique was described in ASME B46.1-1985 and is not typically used with current technology.

NONMANDATORY APPENDIX B
CONTROL AND PRODUCTION OF SURFACE TEXTURE

B-1 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 specifications may increase production costs and reduce the emphasis on other more critical surface specifications.

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

(c) Working surfaces such as those in bearings, pistons, gears, and sealed joint flanges are typical of surfaces that require control of the surface characteristics to perform optimally. 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.

(e) Specifications of different roughness parameters have different sensitivities to variation in the machining process. For example, peak and valley based parameters (e.g., *Rz*, *R*max, etc.) are more sensitive to variation in machining process conditions than parameters which average all profile data (e.g., *Ra*).

B-2 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 B-1 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.

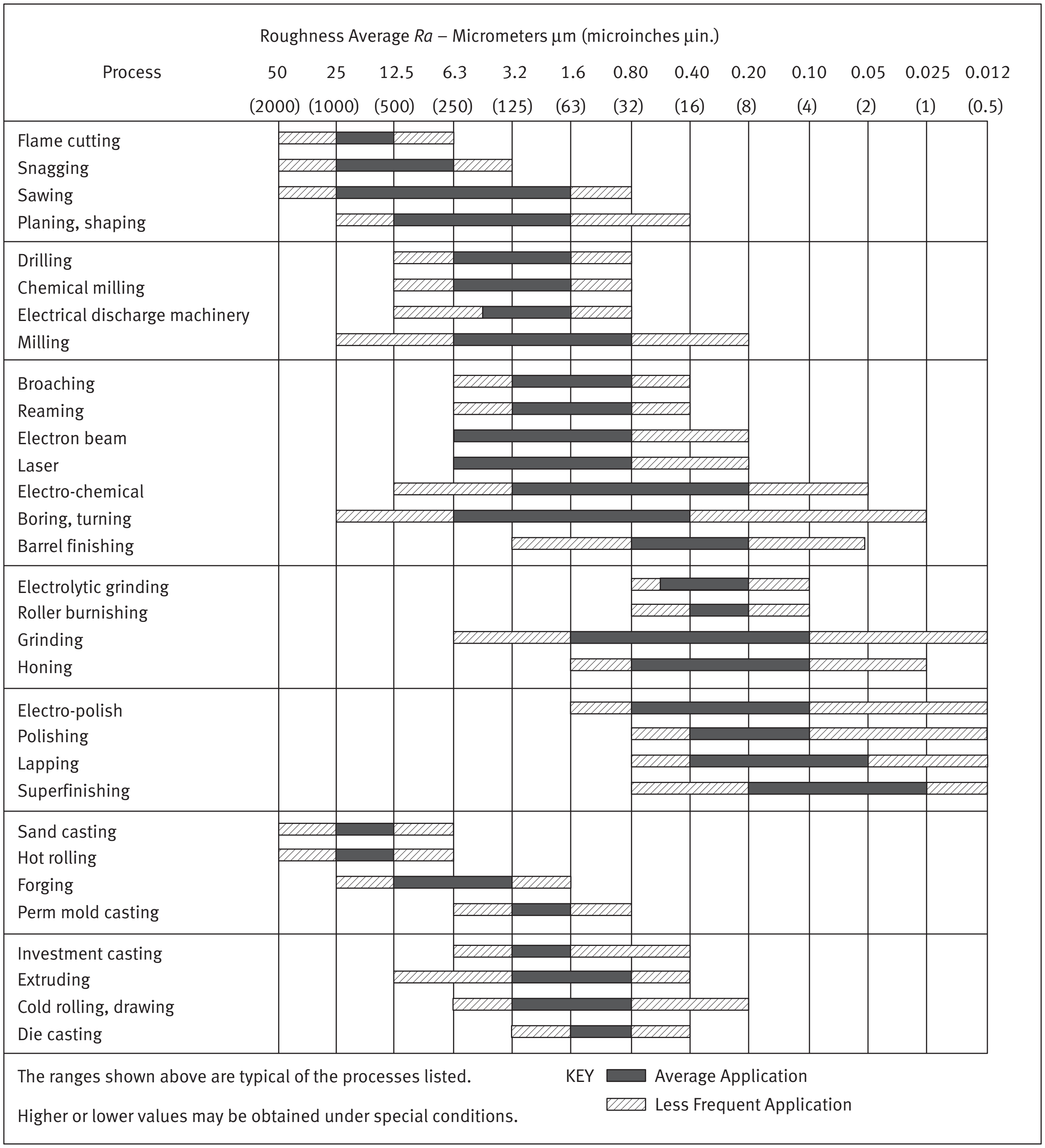
(c) Large amplitude waviness may be an undesirable surface condition that represents significant undulations, in addition to roughness, of the surface, typically resulting from unintended tool or workpiece vibration. Some fabrication processes are prone to the generation of waviness and some functional surfaces require the control of waviness. Examples include parts subject to contact loading such as bearings, gears, and some sealing surfaces. Waviness is also a consideration in the appearance of decorative components such as automotive body panels, surfaces of appliances, etc.

B-3 INSPECTION

(a) ASME B46.1 explains the interpretation of specifications of surface finish on drawings. Although this Standard 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 instruments permit the accurate measurement of characterization parameters for surfaces generated in production. The precision reference specimens provide an accurate means of calibrating the measuring instruments. The roughness comparison specimens allow engineers or designers to obtain an approximate idea of the surface textures produced by various machining processes.

(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, the surface texture of pilot specimens should be measured by calibrated instruments. Pilot specimens are of the same size, shape,

Fig. B-1 Surface Roughness Produced by Common Production Methods



material, and physical characteristics as production parts from the same machine setup which may make it possible to determine by sight or feel when production parts 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, because reflectivity is dependent on such factors as the specular properties of the material, the lighting conditions, viewing angle, roughness, irregularity spacing and color, as well as roughness height. The presence of waviness may affect the appearance of a surface because long spatial wavelength features are often more readily observable with the unaided eye than shorter spatial wavelength roughness features.

B-4 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) Casting porosity is an internal material characteristic which impacts the machined surfaces generated from castings. Pores which are intersected by the machined surface represent flaws or singularities which are often controlled by specification of maximum size, number, or minimum spacing. The presence of surface porosity can greatly influence the filtered roughness profile and calculated roughness parameters. Evaluations of roughness or waviness may be limited to areas free of such porosity or require pore regions to be removed from the evaluated profile. Manual evaluation of the unfiltered surface profile or an alternate surface measurement method may be required to assess porosity or other singular features such as scratches, dings, dents, or machining steps.

(d) 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 "SAE J435C — Oct. 2002 (Society of Automotive Engineers) Automotive Steel Castings" describes methods of evaluation for steel casting surface texture used in the automotive and related industries.

NONMANDATORY APPENDIX C
A REVIEW OF ADDITIONAL SURFACE MEASUREMENT METHODS

C-1 INTRODUCTION

This Nonmandatory Appendix highlights certain surface measurement techniques other than those described in ASME B46.1.

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 U.S. and other countries.

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 the following:

(a) optics, including microscopy, reflectance measurement, image analysis, and holography

(b) electron optics (both scanning and transmission electron microscopy)

(c) nondestructive testing methods including ultrasonics, eddy current, and capacitance

(d) precision dimensional measurement including air gauging and measurement of form

(e) surface integrity measurements [see para. C-5(a)] 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

(f) chemical characterization including electron and ion spectroscopy and analysis

For other commonly used methods, see Nonmandatory Appendices E and F.

C-2 OPTICAL METHODS

C-2.1 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 following formula:

$$d = \frac{k\lambda_0}{NA}$$

where

k = a value between 0.6 and 0.8 depending on the instrument characteristics

λ_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-2.2 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. C-5(b)] in 1931 and has since been refined and modified.

(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 μm (40 μin.) (see Fig. C-1).

(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.

C-2.3 Optical Reflectance Measurement (Glossmeters)

Relative measurements can be made by obliquely illuminating a test surface with either single or multiple wavelengths of light and measuring the ratios of specular to scattered intensities. Glossmeters operate on this principle [see para. C-5(c)] and Fig. C-2.

Fig. C-1 Schmaltz Profile Microscope

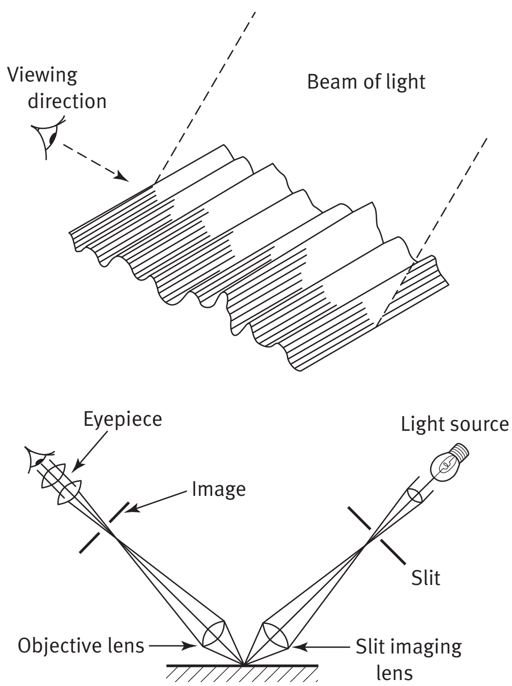
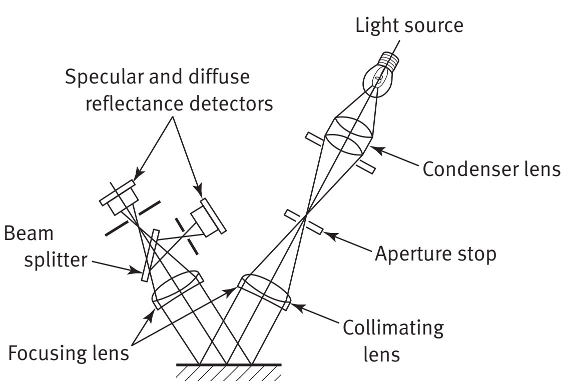


Fig. C-2 Reflectance Measurement



C-2.4 Double Beam Interferometry: Circular Path Profiler

The circular path profiler developed by Sommargren [see paras. C-5(d) and (e)] is shown in Fig. C-3. 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.

C-2.5 Multiple Beam Interferometry

(a) In this method, pioneered by Tolansky [see para. C-5(f)], the side of the reference flat facing 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. C-4).

(b) If the distance between the surfaces is small enough, on the order of a few wavelengths of light, 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 inteferometer. 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 mirror can become damaged, and must be replaced if necessary.

C-2.6 Differential Interference Contrast or Nomarski Microscope

This instrument [see para. C-5(g)] 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 (i.e., displaced) 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. Figure C-5 is a differential interference contrast photograph of an automobile engine cylinder wall before run-in.

C-2.7 Differential Interferometry

(a) This system is similar to differential interference contrast. However, the amount of shear of the two

Fig. C-3 Schematic Diagram of Circular Path Profiler

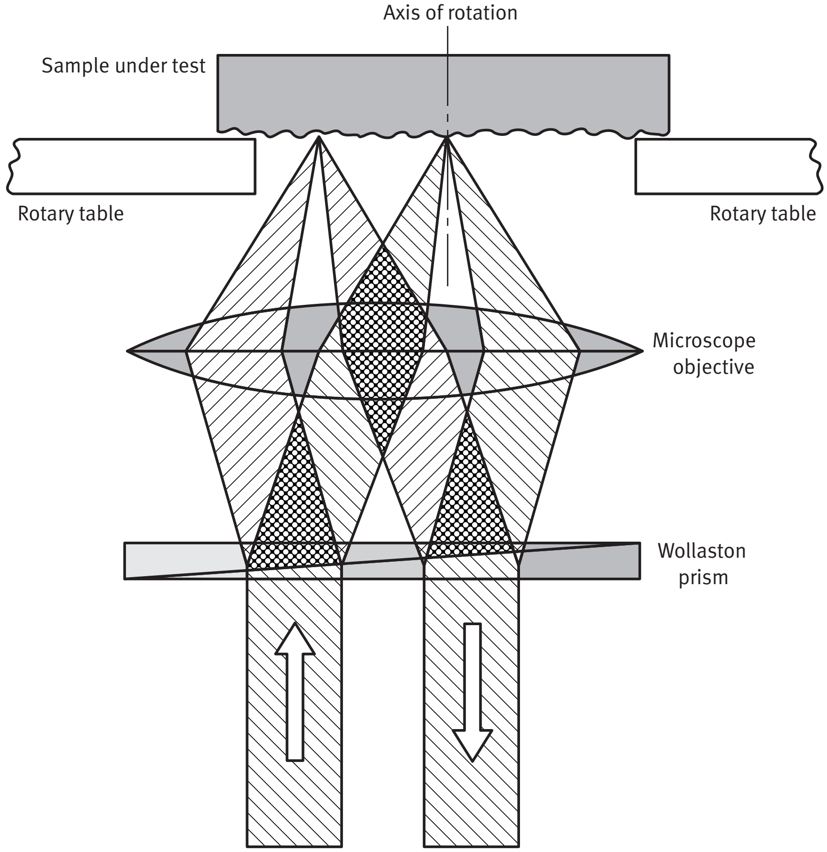


Fig. C-4 Multiple Beam Interferometer

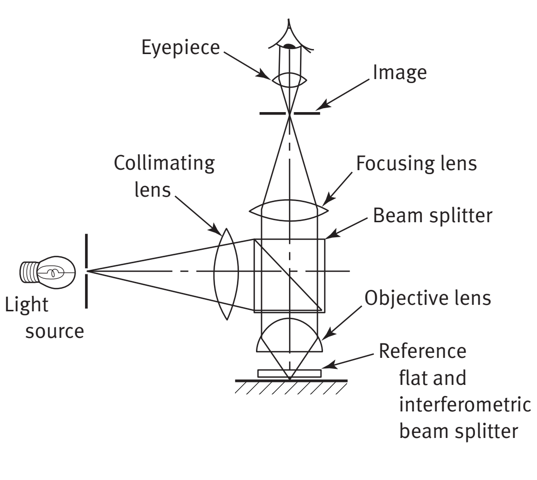


Fig. C-5 Differential Interference Contrast Photograph of Automobile Engine Cylinder Wall

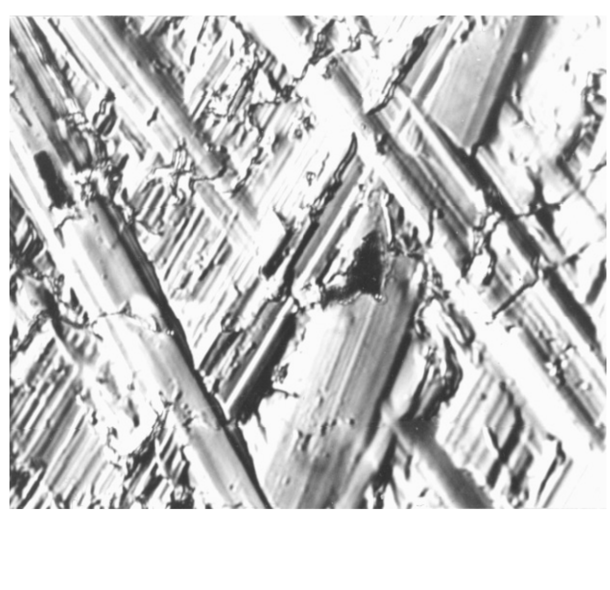
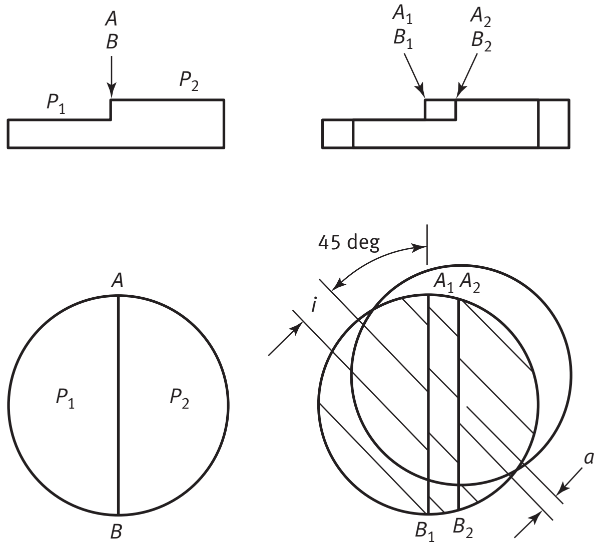


Fig. C-6 Differential Interferometry



images is much greater, generally 20% of the field 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 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 monchromatic light can be used for any magnification. Precise measurements 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. C-6, if, for instance, a simple surface has two planar 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 as follows:

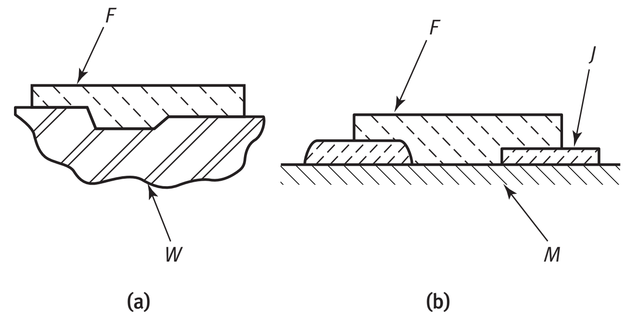
$$\frac{a}{i} \times \frac{\lambda_o}{2}$$

where

a = fringe displacement caused by the step
i = spacing between adjacent fringes
λ_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.

Fig. C-7 Zehender Method



C-3 REPLICAS

(a) When the surface itself cannot be examined directly, negative impressions (replicas) are sometimes used. Although all replicas initially contact the workpiece, different types of replicas are made for contacting and noncontacting measurements.

(b) Replicas for Contacting Methods. When a typical stylus instrument cannot be used on a surface because of its shape, location, or softness, a replica may be made that can then be measured with a stylus instrument. Cautions regarding the replica material include its hardness after curing, its shrinkage, and its fidelity. However, in certain cases it is possible to duplicate surface details down to the 2 nm height range [see para. C-5(h)].

(c) Replicas for Noncontacting Methods. No hardness or wear resistant properties are required when replicas are examined using noncontacting methods. Therefore, softer materials such as coatings or films may be used for replication.

(d) Zehender Technique for Extending Utilization of Interference Microscopes [see para. C-5(i)]. On rough surfaces the interference fringes are deflected to such a high degree that their course cannot be followed. By means of the Zehender method such rough surfaces can, in effect, be demagnified. For this purpose, a transparent film replica is made of the surface to be examined. The replica F is made by pressing a piece of acetate film against the work surface W which has been wet with a drop of acetone [see Fig. C-7(a)].

After drying, the film is placed in a Zehender chamber that consists of a mirror and cover glass combination with a replica in between. The combination is viewed under a two-beam type of interference microscope at a suitable magnification, not exceeding 200X. Figure C-7(b) is a schematic diagram that shows the principle of the demagnification effect. The film replica (F), which has a refractive index n_f, is placed on the mirror M with the impressed features downward. The medium J is a liquid which is placed between the film and the mirror and has a refractive index n_j. In this arrangement, the deflections of the interference fringes caused by the surface topography are reduced by the factor $(n_f - n_j)$ as compared with those obtained by viewing the surface directly.

If $n_f = 1.51$ and $n_j = 1.41$, then the fringe deflections will be only one-tenth of those obtained without a replica. By choosing a suitable immersion fluid, the sensitivity of the interference method can be adapted to the roughness of the surface to be evaluated. Commercial Zehender replica kits include the necessary reference mirrors, replica films, and immersion fluids. An important secondary advantage of the technique is that the replica can be taken on a curved surface such as an involute gear tooth and then flattened out with a cover glass so that it conforms to the shape of the reference mirror. Pits, cracks, and other discontinuities can then be examined on curved surfaces. Considerable skill and patience are required for meaningful results.

C-4 ELECTRON MICROSCOPE METHODS

C-4.1 Transmission Electron Microscope (TEM)

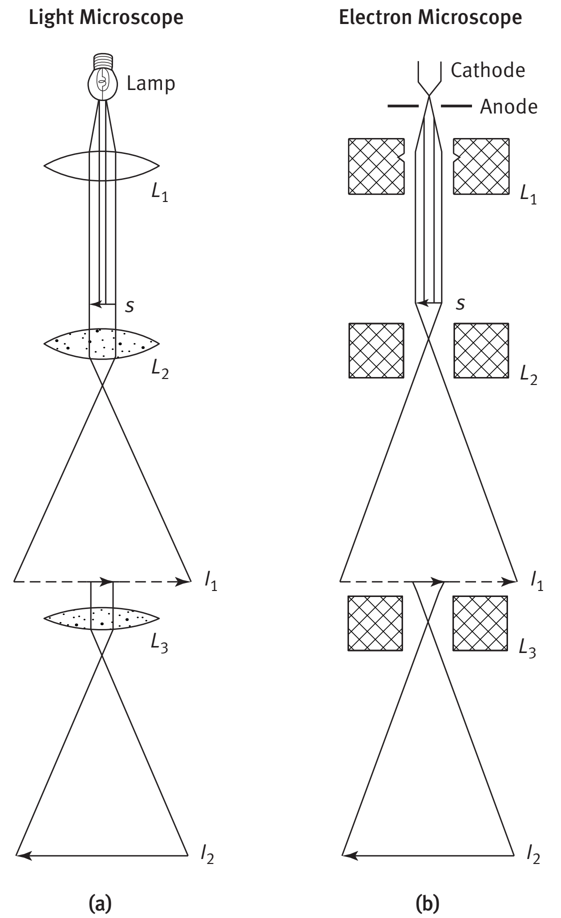
It should be noted that TEM's are frequently used to look at microstructures where the term "texture" is used to refer to grain orientation and not surface topography.

(a) The TEM is fundamentally analogous to an optical transmission microscope where, instead of photons of light, electrons illuminate the sample, as illustrated in Fig. C-8. The illuminating beam of electrons is focused by an electromagnetic condenser lens (or lenses) shown in the diagram as L_1, onto the specimen (S). Variations in electron density of the sample impede or allow the electrons to pass through an objective lens (L_2) and subsequently through a projector lens (L_3) to form an image (I_2) on a fluorescent screen, photographic plate, or other capturing method. Figure C-8 is only a schematic of the principal components of a TEM and should not be interpreted as inclusive of all TEM designs. Additional intermediate condenser and projector lenses are often used.

(b) The low penetrating power of electrons and their short wavelength result in many differences between optical and electron microscopes. The low penetrating power of electrons requires that the specimen and the entire electron path be in a high vacuum region with absolute pressures of 10^{-5} Torr or less. Specimens must have a thickness of 100 nm (4 μin.) or less. However, the extremely short wavelength of the electron, approximately 0.0025 nm for an accelerating voltage of 200 kV, allows for high spatial resolution (0.2 nm to 0.4 nm), and useful magnifications up to 5×10^5.

(c) To study surface topography, a suitable replica whose thickness is less than 100 nm (4 μin.) must be made of the surface of the test specimen. Quantitative information about the topography may then be obtained

Fig. C-8 Comparison of Optical and Transmission Electron Microscope



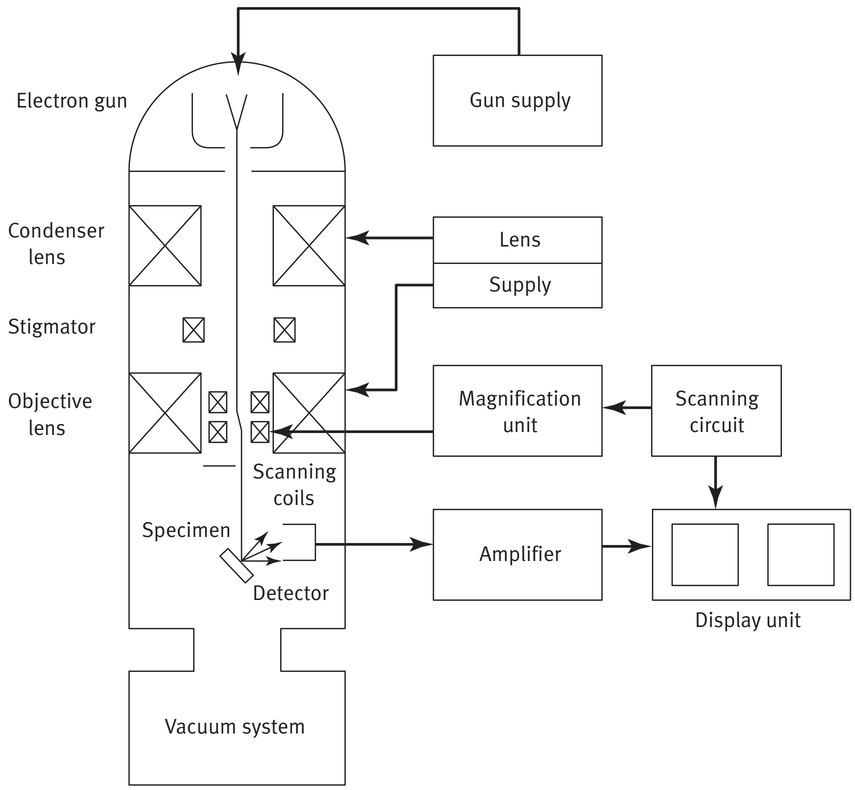
by taking two measurements, with the specimen being tilted through an angle of about 8 deg (0.14 rad) between the two measurements. Surface profiles and contour maps may be constructed from the two measurements with the aid of instrument software or a stereoscope. Height resolution is significantly limited by the measurement of tilt angle, stereoscopic interpretation, and the replication procedure.

C-4.2 Scanning Electron Microscope (SEM)

The SEM can provide an image that is based on topographic contrast which can be used for surface texture measurements using stereoscopic pairs.

(a) In contrast to the TEM, in which the area of examination is uniformly illuminated by a broad beam of electrons, a SEM [see paras. C-5(j), (k), and (l)] uses a scanning beam of electrons finely focused on the specimen surface. The image of the specimen is derived from secondary and backscattered electrons emitted from the specimen and collected by a detector (or detectors) placed in proximity to the specimen. The images formed may then be used to obtain textural information about

Fig. C-9 Diagram of Scanning Electron Microscope



the specimen surface. A schematic diagram of an SEM is shown in Fig. C-9. Similarly, as stated above, Fig. C-9 is only a basic schematic of the principal components of an SEM and should not be interpreted as inclusive of all SEM designs. A number of different lens designs and electron sources are possible.

(b) The advantages and limitations of using an instrument having an electron beam, discussed in para. C-4.1 for the TEM, also apply to the SEM. However, since the SEM depends primarily upon backscattered or emitted electrons, there are no stringent requirements on specimen thickness.

(c) The extraction of quantitative information about surface topography from the many possible outputs of an SEM is difficult and complex, since contrast in the displayed image is affected by many factors (e.g., electric field enhancement at sharp edges, crystallographic orientation, and the point-to-point variation in atomic composition of the specimen). Nevertheless, because of its excellent spatial resolution (as small as 1 nm) and its large depth of focus, the SEM is a convenient and frequently used tool to examine the surfaces of engineering specimens. Stereoscopic pairs of images similar to those described for the TEM are one way to achieve topographic information.

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NONMANDATORY APPENDIX D
ADDITIONAL PARAMETERS FOR SURFACE CHARACTERIZATION

This Nonmandatory Appendix discusses surface texture parameters other than those described in Section 1 of this Standard, which may be useful in surface quality research and certain areas of process control. It also adds information about the autocovariance function defined in Section 1. Finally, it discusses the uniformity of surfaces and the variation of measured parameters.

D-1 INTERNATIONAL STANDARDS AND PARAMETERS

D-1.1 Average Peak-to-Valley Roughness *R* and Others

This general term is intended to include those parameters that evaluate the profile height by a method that averages the individual peak-to-valley roughness heights, each of which occur within a defined sampling length[1] (see Fig. D-1).

D-1.2 Average Spacing of Roughness Peaks *AR*

This is the average distance between peaks measured in the direction of the mean line and within the sampling length. The term *peaks* has a wide variety of interpretations; therefore, this parameter must be evaluated according to a specific standard[1] (see Fig. D-2).

D-1.3 Swedish Height of Irregularities (Profiljup), *R* or *H*

This is the distance between two lines parallel and equal in length to the mean line and located such that 5% of the upper line and 90% of the lower line are contained within the material side of the roughness profile (see Fig. D-3). This parameter is the same as *Htp* (5, 90) (see para. 1-4.3).

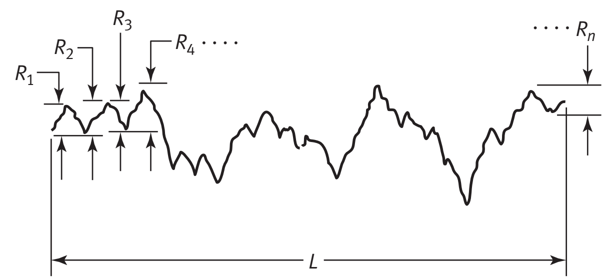
D-2 AUTOCOVARIANCE FUNCTION

(a) The autocovariance function is a measure of similarity between two identical but laterally shifted profiles. For a particular shift length, its value is obtained by multiplying the shifted and unshifted waveform over the overlapping length, ordinate by ordinate, then calculating the average of these products. The formula for computing ACV from a profile is given in Section 1 of this Standard.

(b) The root-mean square roughness (*Rq*) of the profile is equal to the square root of the ACV value at the

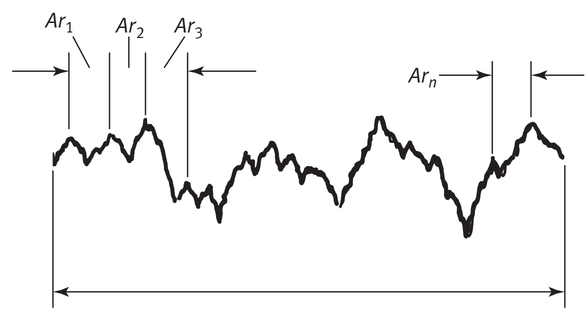
[1] A practical implementation is described in ISO 12085-1996.

Fig. D-1 Average Peak-to-Valley Roughness



$$R = \frac{R_1 + R_2 + R_3 + \cdots\cdots R_n}{n}$$

Fig. D-2 Average Spacing of Roughness Peaks



$$Ar = \frac{Ar_1 + Ar_2 + Ar_3 + \cdots\cdots Ar_n}{n}$$

Fig. D-3 Swedish Height of Irregularities

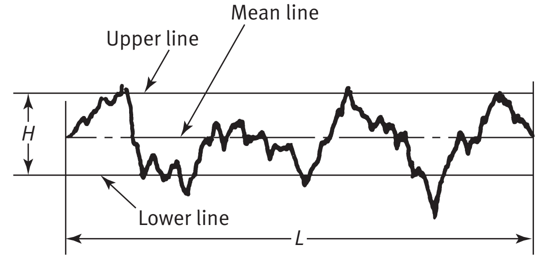
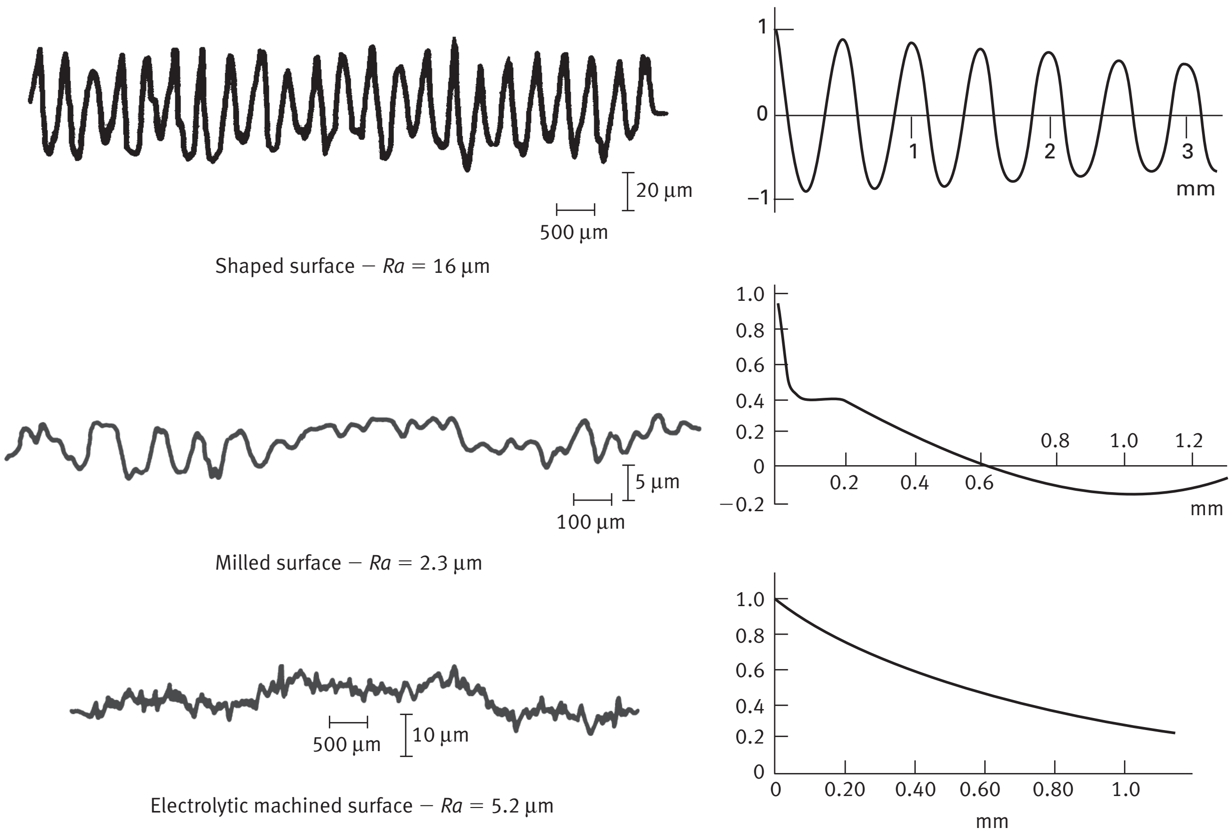


Fig. D-4 Measured Profiles and Their Autocorrelation Functions



zero-shift position. The correlation length (ASME B46.1, Section 1) of the profile is determined as the shift distance where the ACV, or its upper boundary envelope, first drops to a specified fraction of the ACV when evaluated at the zero shift position. When two points on a profile have a spacing greater than the correlation length, they are considered to be independent and generally result from separate steps in the surface forming process. Figure D-4 shows profiles of surfaces obtained by three processing methods along with the normalized autocovariance function of each profile. The normalized autocovariance function is called the autocorrelation function (ACF) and is also described in Section 1 of this Standard.

D-3 UNIFORMITY OF SURFACE

(a) The various surface texture parameters deal with the evaluation of a single surface profile. However, no surface is truly uniform. Therefore, no single surface roughness profile or parameter measurement of that profile is truly representative of the entire surface itself.

(b) To characterize the surface texture of an area more completely, it is necessary to analyze a number of profiles. This analysis provides information on the mean value of the parameter for the surface and the distribution (standard deviation) in readings that can be expected.

(c) The number of profiles necessary to provide a meaningful measurement is dependent on the intra-surface and inter-surface variation, and the gauge capability of the measurement system relative to the surface quality specification.

(d) Fewer profiles are required to fully characterize a precision reference surface consisting of a regular geometric pattern than, for example, a grit blasted sheet metal surface with randomly spaced pits of varying sizes.

D-4 GENERAL REFERENCES ON SURFACE TEXTURE MEASUREMENTS

General references may be found in the Engineering Index (1943–onward), under appropriate headings, such as Metals Finishing, Surface Roughness Measurement, and Metals Testing.

D-4.1 Surface Texture Measurement and Instrumentation

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NONMANDATORY APPENDIX E
CHARACTERISTICS OF CERTAIN AREA PROFILING METHODS

This Nonmandatory Appendix describes the operating principles and performance of several area profiling techniques. Due to the advancement of technology, the performance aspects discussed here may not necessarily be up to date.

E-1 IMAGING METHODS

E-1.1 Vertical Scanning Interferometric Microscopy

E-1.1.1 Description. This type of microscope is schematically similar to the phase measuring interferometric microscope as shown in Fig. 8-1. However, these systems typically use a white light source. The microscope will typically scan either the sample or the optical system normal to the surface of the sample. During the scanning motion, the resulting interference fringe patterns are analyzed on a pixel-by-pixel basis to determine the height in the vertical scan where the fringe contrast is highest. By establishing the height corresponding to the maximum fringe contrast for each pixel, a map of the surface heights is established.

E-1.1.2 Performance

(a) Range. Vertical scanning interferometric microscopes are applicable for surfaces with *Ra* smaller than about 20 μm. The evaluation area ranges up to about 6 mm × 6 mm depending on the magnification of the microscope objective used. In addition, larger evaluation areas may be achieved by combining images of smaller evaluation areas. Vertical scanning interferometric microscopes are limited in ability to measure surfaces with large slopes.

(b) Accuracy. The accuracy of these interferometers is limited by several factors, including the calibration of the scanning mechanism, variations in material properties, and other measurement artifacts [see para. E-3(a)]. The accuracy of these systems can also be affected by contaminants such as oil films on the surfaces. Low reflectivity surfaces may decrease the signal-to-noise ratio of the measurement unless compensating circuitry or mechanisms are included in the instrument. In addition, if the surface slope is too large, the reflected light signal will not enter the detection system.

(c) System Noise and Height Resolution. The height resolution is limited by the system noise, which can be less than 1 nm, or by the quantization increment of the vertical scanning system. The system noise is affected by the noise of the detector electronics and environmental factors. To minimize the environmental effects, the instruments may be mounted on vibration isolation tables. The height resolution can be estimated by taking the difference between successive topography measurements and calculating the *Rq* value of the resulting *difference topography*. Signal averaging can be applied to reduce the system noise to less than 1 nm.

(d) Spatial Resolution. The spatial resolution is determined by the same considerations as the phase measuring interferometric microscope (see Section 8).

E-2 SCANNING METHODS

E-2.1 Optical Focus-Sensing Systems

E-2.1.1 Description. The principle of operation is shown in Fig. E-1 [see para. E-3(b)]. A converging optical beam is reflected from the surface. The instrument senses whether the optical beam is focused on the surface and records the height at which this focus occurs. The beam is raster scanned and produces profile or area topography measurements by recording the focus location as a function of lateral position over a sample.

Many techniques have been used to sense focus. Customarily, they produce an error signal when the beam is out of focus. The error signal is then used to displace an objective lens to the correct focus position. The position of the sensor at best focus is recorded as the height of the surface at that location. These servo systems are similar to those used in optical read-write memory systems.

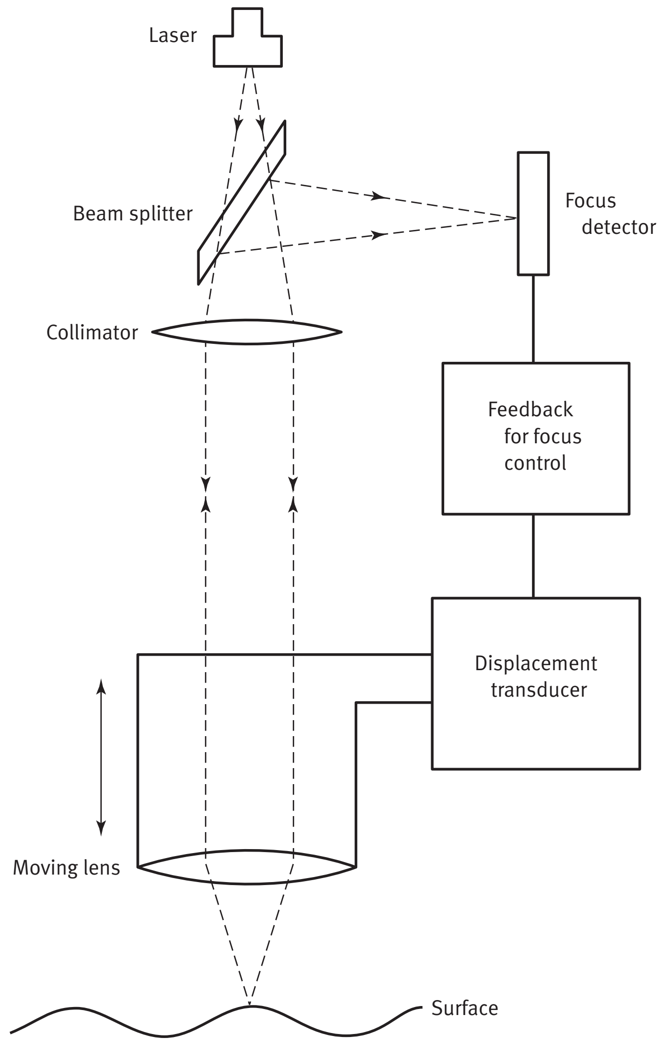
E-2.1.2 Performance

(a) Range. The height range is limited by the vertical motion of the focus system, which is on the order of 1 mm. The evaluation length is limited by the *x-y* motion system used and can be on the order of 10 mm to 100 mm in each direction.

(b) Accuracy. Both specular and diffuse samples may be measured with these systems. However, the accuracy of these systems can be affected by the presence of contaminants such as oil films on the surfaces. Low reflectivity surfaces may decrease the signal-to-noise ratio of the measurement unless compensation circuitry or mechanisms are included in the instrument. In addition, if the surface slope is too large, the reflected light signal will not enter the detection system.

(c) System Noise and Height Resolution. A height resolution of 10 nm is achievable. The height resolution may be estimated by measuring the apparent rms roughness

Fig. E-1 Schematic Diagram of an Optical Focus-Sensing Instrument



of a sufficiently smooth optical surface. The system noise arises from a number of sources such as mechanical vibration and acoustical noise.

(d) Spatial Resolution. The spatial resolution may be limited by the response of the feedback circuit to control the focus mechanism or by the spot size of the light beam. A spatial resolution of about 0.8 μm can be achieved in a high magnification system.

E-2.2 Nomarski Differential Profiling

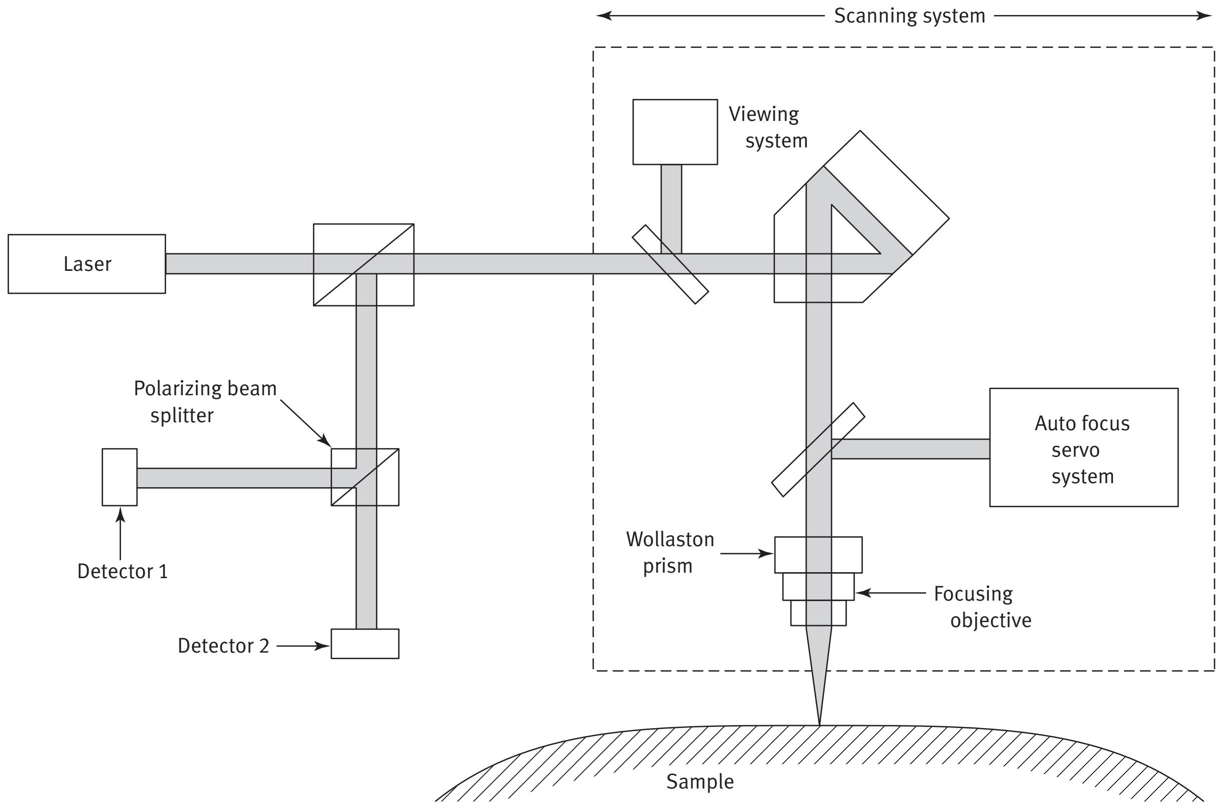
E-2.2.1 Description. The Nomarski differential profiler [see para. E-3(c)] is based on the optical technique of Nomarski differential interference contrast (DIC) microscopy. The profiling system (see Fig. E-2) uses a laser light source, a microscope objective, and a birefringent (Wollaston) prism to focus two orthogonally polarized light beams at nearby locations on the surface. The profiling direction is aligned with the direction of the beam separation.

After reflection from the surface, the two beams again pass through the Wollaston prism and recombine. The beam is then split again by a polarizing beamsplitter and directed to two detectors that monitor the phase shift of the reflected beams. This phase shift arises from the difference in the vertical height of the two adjacent areas from which the two beams are reflected, and therefore, is directly proportional to the local surface slope. The integration of the slope data provides information on topographical height variations. The sensor head is rastered across the surface to generate a series of equally spaced two-dimensional profiles of the surface slope. This type of system is capable of measuring surfaces that reflect a small percentage of the focused laser light, typically down to about 4%.

E-2.2.2 Performance

(a) Range. The evaluation length of Nomarski profiling systems is limited by the translation capability in

Fig. E-2 Schematic Diagram of Nomarski Differential Profiler



the x and y directions and may be as large as 100 mm in each direction.

(b) Accuracy. The accuracy of the rastering optical profiler is determined by the accuracy of the reference slope standard or reference height standard used in the calibration and by the variation of the optical phase change on reflection over the surface. Because the recorded profile is an integration of differential heights, there is a certain amount of vertical drift in the measured surface profiles, which increases with traverse length. However, for profiles of 1 mm length, the vertical drift is on the order of the system noise. If the surface slope is too large, the reflected signal will not enter the detection system.

(c) System Noise and Height Resolution. Because the technique is based on the difference in optical path length of two light beams reflected from nearly the same place on the surface, it is relatively unaffected by specimen vibrations. The height resolution depends on the electronic noise and the number of quantization levels in the digitization system. System noise is on the order of 0.01 nm.

(d) Spatial Resolution. The spatial resolution of this instrument depends on the choice of focusing objective and the sampling intervals used during rastering. Spatial resolution of about 0.8 μm can be achieved in a high magnification system.

(e) Other Considerations. Because relative heights between successive profiles are not monitored, the recorded topography represents a collection of two-dimensional profiles and is not necessarily a complete representation of the three-dimensional topography.

E-2.3 Stylus

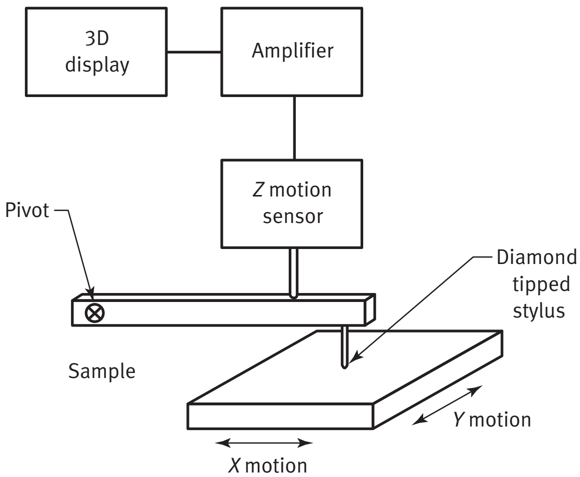
E-2.3.1 Description. Contacting stylus instruments used for surface profiling methods may be adapted for area profiling by adding a second axis of motion, as shown in Fig. E-3, to provide rastering of the surface profiles [see paras. E-3(d) and (e)]. Characteristics of stylus instruments are discussed in Sections 3 and 4 of this Standard.

E-2.3.2 Performance

(a) Range. The evaluation length of these instruments is limited by the length of travel of the motion system, and ranges as large as 300 mm have been realized. The height range of the transducer may be as large as 6 mm, but there is an engineering tradeoff between range and resolution.

(b) Accuracy. The accuracy of stylus instruments is limited primarily by the accuracies of the standards used to calibrate the vertical travel and by the linearity of the transducer. The latter is typically better than 1% (i.e.,

Fig. E-3 Area Scanning Stylus Profiler



variations in measured step height or *Ra* values are less than 1% over the height range of the transducer).

(c) System Noise and Height Resolution. The height resolution depends on the sensor electronics and environmental noise. For single profile stylus instruments, the noise has been measured to be as small as 0.05 nm under certain conditions [see para. E-3(f)]. The spatial resolution may also be limited by the sampling interval (see para. 1-3.4).

(d) Spatial Resolution. The spatial resolution depends on the area of contact of the stylus tip with the surface and can have dimensions as small as 0.1 μm [see para. E-3(g)]. The spatial resolution may also be limited by the sampling interval (see para. 1-3.4).

E-2.4 Scanning Tunneling Microscopy

E-2.4.1 Description. The scanning tunneling microscope (STM) works on the principle of electron tunneling [see paras. E-3(h) and (i)]. A tunneling current is produced when a sharpened conducting tip is brought to within a nanometer of a conductive surface and a voltage is applied between them. The tunneling current decreases by roughly an order of magnitude for every 0.1 nm increase in the gap spacing and hence is very sensitive to any change in the gap spacing. Figure E-4 shows a schematic diagram of an early STM design. The probe tip is mounted to a three-axis piezoelectric transducer (PZT) scanning mechanism. A feedback system detects the tunneling current and drives the z axis PZT to maintain a constant tunneling current and gap spacing between the probe tip and the surface. The x and y axis PZTs perform raster scanning of the test sample to build up a three-dimensional image of the surface topography. Later designs generally use a piezo tube scanner to achieve the three axes of motion.

Scanning tunneling microscopy is a noncontact surface profiling technique. However, damage to the test surface is possible because of the strong electric field and high current densities and because of the potential for accidental mechanical contact. The use of STM is generally limited to electrically conducting surfaces.

E-2.4.2 Performance

(a) Range. The evaluation length of the instrument is limited by the length of accurate travel of the scanning system. Useful results have been obtained with ranges as high as 500 μm. The height range is limited by the travel of the z axis PZT and has typical values on the order of 2 μm.

(b) Accuracy. Probe tip geometry can affect imaging accuracy. Artifacts arising from tunneling at multiple places from a single probe tip can confuse the interpretation of the data. The test surface can have localized regions having differing electrical properties, a factor which produces erroneous structure in the surface profile at the subnanometer level. In all three directions the accuracy is affected by the linearity of the PZT transducers. Their sensitivity (distance traveled/voltage input) can vary up to a factor of two or more over their range. Therefore, calibration of the PZTs is an important consideration. To calibrate the scanning mechanism, structures with known periodicity and height can be profiled.

(c) System Noise and Height Resolution. The height resolution is typically of an atomic scale (0.1 nm or less) and is determined primarily by the overall stability of the gap spacing. The gap width stability is mainly limited by vibration and thermal drift. An especially high degree of vibration isolation is therefore required. Thermal drifts of more than about 1 nm/minute can distort an image, which might take several minutes to acquire. Therefore, the sample and stage should be isolated from any heat source.

(d) Spatial Resolution. Atomic scale spatial resolution (0.2 nm or better) is typically achievable. Tip sharpness and lateral vibration are primary factors which limit spatial resolution. Lateral drift of the PZT transducers can also be significant. In addition, as the evaluation length of the system is increased, the design tradeoffs cause an accompanying degradation in spatial resolution.

E-2.5 Atomic Force Microscopy

E-2.5.1 Description. The atomic force microscope (AFM) is similar to a contacting stylus instrument but also uses features of the STM design. The sensor primarily detects the mechanical force between a probe tip and a sample surface. The probe tip, often having a radius less than 100 nm, is mounted to a small cantilever. The repulsive or attractive forces between the sample and the probe tip deflect the cantilever. The deflection of the cantilever can be sensed to subnanometer resolution using any one of several techniques. These include an optical lever technique using a laser beam [see para. E-3(j)] (see Fig. E-5) and a piezoelectric technique.

Fig. E-4 Basic Structure of an Early STM

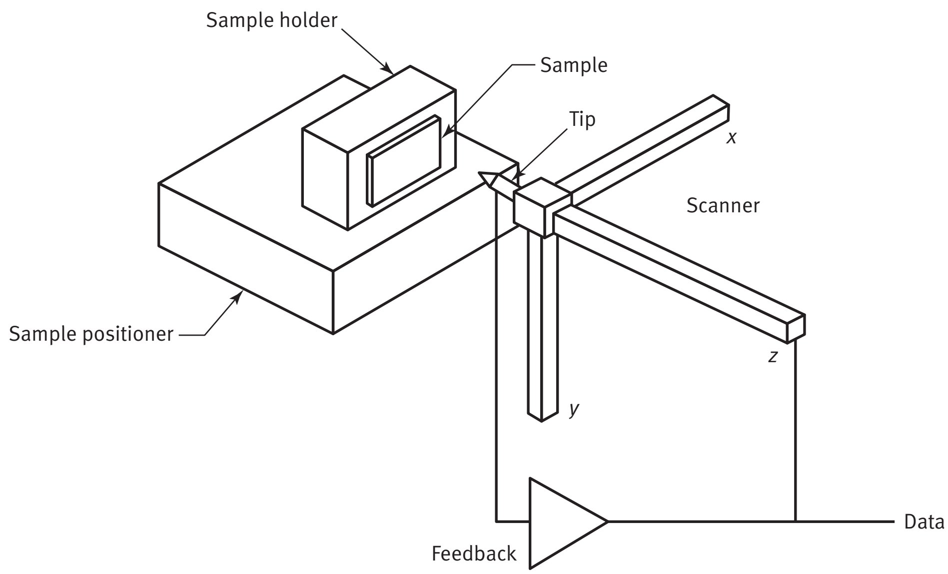
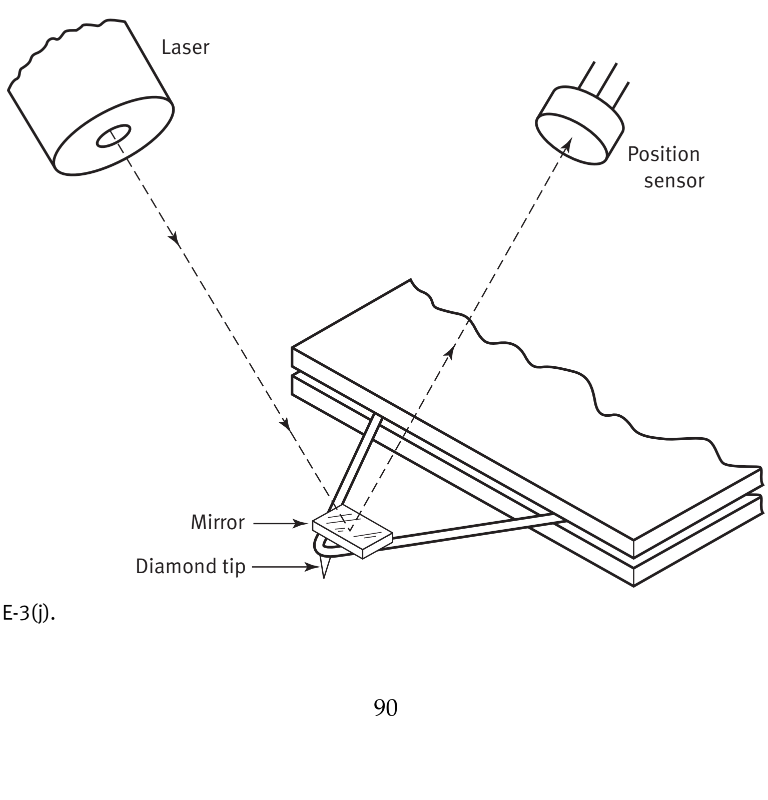


Fig. E-5 Schematic Diagram of an Atomic Force Microscope With an Optical Lever Sensor
[Reprinted by permission of the American Institute of Physics from S. Alexandar, et al., "An Atomic-Resolution Atomic-Force Microscope Implemented Using an Optical Lever," *Journal of Applied Physics* 65 (1989): 164.]



GENERAL NOTE: See para. E-3(j).

The sample or probe tip is usually mounted to a piezoelectric tube scanner. A feedback loop to the *z* axis of the scanner keeps the cantilever deflection constant during scanning. The probe tip, when brought close to the surface, first begins to feel an attractive force and then the strong repulsive force of contact. AFMs are mostly operated in either the repulsive (contact) mode or an oscillatory, intermittent contact mode.

The AFM sensing mechanism makes possible the measurement of both electrically conducting and nonconducting materials. AFMs can operate in air as well as in vacuum or liquid media.

E-2.5.2 Performance

(a) Range. The vertical and lateral ranges are limited by the PZT transducers and are about the same as those of STMs.

(b) Accuracy. As with STMs, the accuracy of profile depends to a large extent on the nonlinearities of the PZT materials. Calibration standards may be used to calibrate both the vertical and lateral travel. The repeatability of the PZT stage determines the lateral measurement repeatability.

(c) System Noise and Height Resolution. The height resolution is determined by the degree to which the probe tip-to-surface distance is maintained constant during scanning. This is determined in part by the resolution of the method for sensing the deflection of the cantilever and may be as small as sub 0.1 nm. Vibration isolation is also required, but perhaps not to the degree required for the STM.

(d) Spatial Resolution. The primary determinant of spatial resolution in the repulsive mode is the size of the contact area of the probe tip with the surface. Under certain conditions, individual atoms have been resolved by an AFM. For operation in the attractive mode, the spatial resolution is determined by the spacing between the probe tip and the sample. Spatial resolution on the order of 5 nm has been achieved using the attractive mode.

E-2.6 Confocal Microscopy

Confocal microscopy, originally referred to as "double focusing microscopy," was first described by M. Minsky[1, 2] in 1957. The depth-discrimination effect of confocal microscopy is achieved by the use of pinhole illumination (or other method of achieving structured illumination) and pinhole detection as shown in Fig. E-6. After passing through a beam splitter, light passes through a microscope objective and illuminates the target surface (first focal point). Light reflected by the surface is decoupled by the beam splitter and directed towards the detector pinhole, which is located on the focus plane of the microscope objective (second focal point). Maximum reflected light intensity is registered on the detector when the microscope objective is focused on the specimen. If the specimen is moved out of focus, a partial suppression of the signal occurs because less reflected light passes through the detector pinhole. By controlled translation of the relative distance in the *z* direction between the specimen and the optics (such that it enters and then leaves the focal plane of the microscope objective), a correlation between the specimen's vertical position and reflected light intensity at the detector can be established.

[1] Minsky M., "Microscopy Apparatus," U.S. Patent 3013467 (19 Dec. 1961, filed 7 November 1957).

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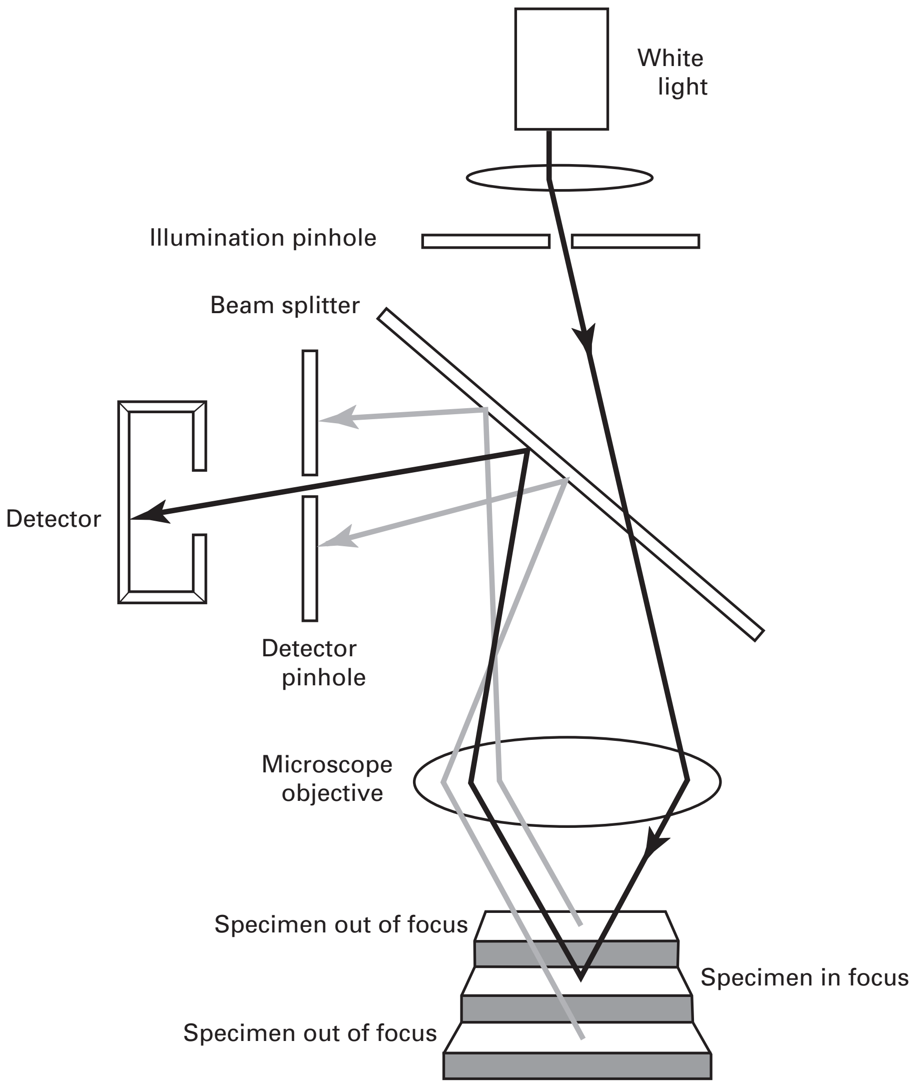
Fig. E-6 Schematic Diagram of a Confocal Microscope



NONMANDATORY APPENDIX F
DESCRIPTIONS OF AREA AVERAGING METHODS

F-1 PARALLEL PLATE CAPACITANCE (PPC)

This technique measures the capacitance of the void space between an electrically insulated sensor and the surface [see paras. F-4(a) and (b)]. The method is generally limited to the assessment of electrically conductive and semiconductive surfaces. A probe comprised of a thin dielectric sheet, metallized on one face (M), is held with its insulating face against a conductive specimen (see Fig. F-1). The capacitance of this interface is measured. The capacitance is inversely related to the mean separation (d) between the insulating face of the probe and the surface of the specimen. The insulated sensor contacts the highest peaks of the surface resulting in larger voids for rougher surfaces than for smoother ones. The measured capacitance caused by these void volumes is a measure of the surface texture.

The capacitance caused by surface texture is equivalent to the capacitance of two parallel conducting plates separated by a dielectric medium (such as air). The capacitance is defined by the following:

$$C = K(A/d)$$

where (see Fig. F-2)
C = capacitance
K = dielectric constant of the medium between the plates
A = area of the capacitor plates
d = average distance between plates

Capacitance instruments are relatively insensitive to surface lay because an area of the surface is assessed. Surfaces to be measured should be free of contaminants. The accuracy of PPC measurement is also dependent on the environmental conditions and on the accuracy of the calibration specimen.

Generally, these instruments are calibrated for each type of surface texture to be measured. For example, the measurement of an electro-discharge machined (EDM) surface would generally require a different instrument setting or calibration reference than the measurement of a milled surface. For calibration, one or more calibrated comparison or pilot specimens should be used. If two are used, their measured values should lie near the ends of the measuring range.

Fig. F-1 Comparison of Roughness Void Volumes

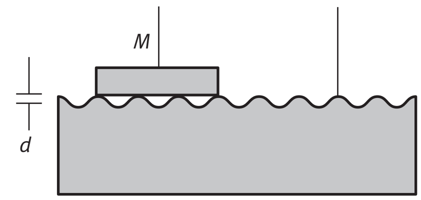
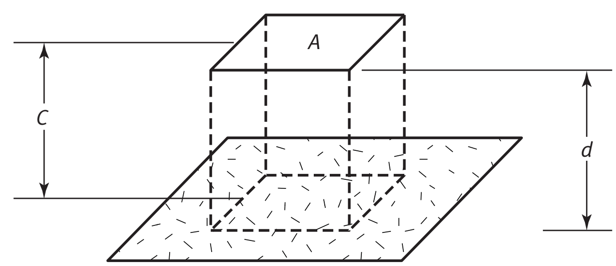


Fig. F-2 Principle of Capacitance Between Parallel Plates



F-2 TOTAL INTEGRATED SCATTER (TIS)

This technique collects and measures light scattered by an illuminated surface [see paras. F-4(c) and (d)]. This method is generally limited to measurements of surfaces with rms roughness much less than the illumination wavelength.

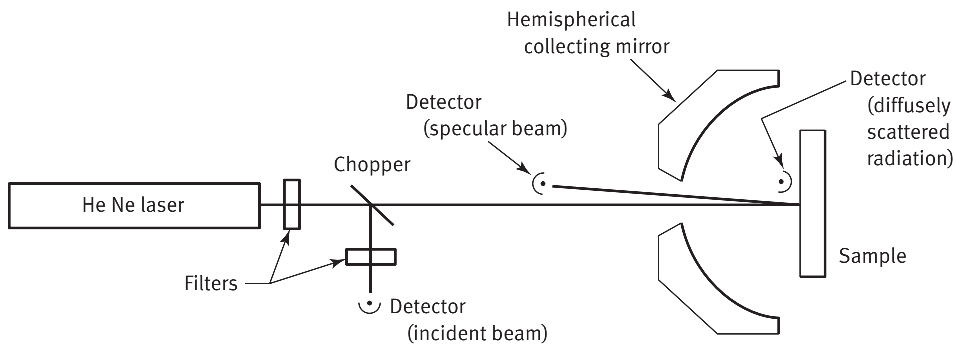
This technique uses a hemispherical shell to collect and measure the scattered light (see Fig. F-3). A laser beam passes through an aperture in the top of the shell and illuminates the surface at near normal incidence. The test surface absorbs a fraction of the light incident upon it and reflects the remaining light. The reflected light consists of a specular and a diffuse component. Smooth surfaces, such as mirrors, reflect a large specular component and a small diffuse component. For rougher surfaces, more of the reflected light is scattered diffusely. The specular beam is transmitted back through the entrance aperture to an external detector. The hemispherical shell focuses the diffusely scattered light to a detector placed near the test surface. The rms roughness is related to the scattered light by the following equation:

$$Rq = \frac{\lambda \sqrt{I_d/(I_s + I_d)}}{4\pi}$$

where
I_d = the integrated diffusely scattered light intensity
I_s = the specular light intensity

Fig. F-3 Schematic Diagram of an Instrument for Measuring TIS

[Reprinted by permission of the Optical Society of American Jean M. Bennett and Lars Mattson, *Introduction to Surface Roughness and Scattering* (Washington, D.C., 1989)]



As is generally the case with roughness measuring instruments, the *Rq* value measured by TIS is a bandwidth limited quantity [see para. F-4(e)]. That is, it measures roughness over a limited range of spatial wavelengths. For TIS, the shortest measurable spatial wavelengths are approximately equal to the wavelength of light. The longest measurable spatial wavelengths are determined by either the illumination spot size or the angular aperture defining the specular beam.

This technique has high repeatability when comparing similar surfaces and allows fast sample throughput. However, the user of these instruments should be aware of two limitations: First, the specular component and near angle portion of the diffusely scattered light are both reflected through the hole of the light-collecting shell and cannot be easily separated. Second, the accurate measurement of I_d and I_s requires the use of both a diffusely reflecting standard and a polished reflectance standard.

F-3 ANGLE RESOLVED SCATTER (ARS)

This technique measures the angular distribution of the light scattered from a surface illuminated by a collimated beam (see Fig. F-4) [see para. F-4(f)]. From this information, the rms roughness or rms slope of the surface can be calculated over an area of the sample.

The measurement of angle resolved scatter (ARS), usually called bidirectional reflectance distribution function (BRDF) [see para. F-4(g)], is similar to that of TIS except that the incident angle of light may be varied, and for each incident angle the scatter may be measured at each angle in the hemisphere. BRDF is therefore a function of four independent coordinates (i.e., the two spherical angles for both the incident and scattered directions with respect to the sample normal).

For surfaces with roughnesses much less than the optical wavelength, the BRDF is related in a straightforward way to the power spectral density of the surface roughness [see para. F-4(h)], and it can be used to assess rms roughness and surface spatial wavelengths. For rougher surfaces the technique may be used as a comparator to estimate rms roughness over the illuminated area provided that the specular beam is detectable [see para. F-4(i)]. In addition, the rms slope of the surface can be calculated from the overall width of the angular scattering distribution [see paras. F-4(j) and (k)]. The optical wavelength may also be altered to examine different spatial wavelength components of the surface.

Since the BRDF is a function of four independent spherical angles, the complete characterization of surfaces by this technique requires a large volume of data. For measurements on smoother surfaces, care must be taken to assure that the area examined on the sample is free of particle contamination. An ASTM standard [see para. F-4(l)] has been developed to foster the uniform performance of instruments that measure BRDF from optical surfaces.

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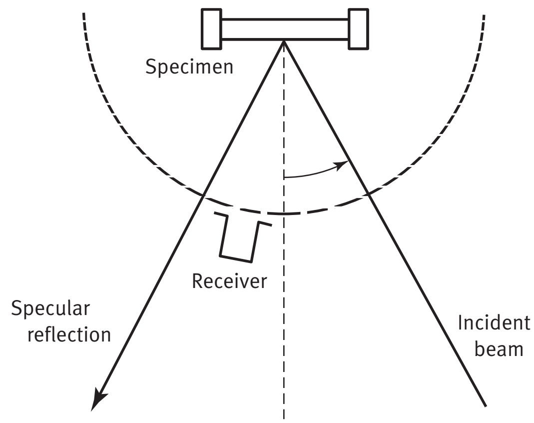
Fig. F-4 Schematic Diagram of an Instrument for Measuring ARS or BRDF

(Reprinted, by permission of the author from John Stover, *Optical Scattering: Measurement and Analysis* New York: McGraw-Hill, 1990, 137.)



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NONMANDATORY APPENDIX G
OBSERVATIONS ON THE FILTERING OF SURFACE PROFILES

There is a clear distinction in the minds of design engineers, quality engineers, and manufacturing engineers between roughness, waviness, and form error in the surfaces of manufactured parts. For some applications, roughness relates to the lubrication retentiveness of the surface, waviness is associated with the load bearing capacity of the surface, and form error is associated with the distortion undergone by the surface during processing or operation. In fabrication, roughness normally stems from texture of the surface caused by the cutting tool edge. These features include, for example, turning marks arising from a single point cutting edge, or fine tracks in an abrasively machined surface arising from the individual grains in the honing stone or grinding wheel. Waviness, however, may arise from the vibrational motion in a machine tool or workpiece, or the rotational error of a spindle. Finally, form error typically results from straightness errors of a machine or deformation of a part caused by the method of clamping or loading during the machining process.

Since these components of surface deviations are attributed to distinct processes and are considered to have distinctive effects on performance, they are usually specified separately in the surface design and controlled separately in the surface fabrication. These components of the surface deviations must thus be distinctly separable in measurement to achieve a clear understanding between the surface supplier and the surface recipient as to the expected characteristics of the surface in question.

In order to accomplish this, either digital or analog filters are used to separate form error, waviness, and roughness in the data representation of the surface that results from a measurement. There are three characteristics of these filters that need to be known in order to understand the parameter values that an instrument may calculate for a surface data set. These are as follows:

(a) the spatial wavelength at which a filter separates roughness from waviness or waviness from form error. This filter spatial wavelength is normally referred to as the cutoff

(b) the sharpness of a filter or how cleanly the filter separates two components of the surface deviations

(c) the distortion of a filter or how much the filter alters a spatial wavelength component in the separation process

In the past, when digital instruments were not readily available, filtration of the roughness profile was primarily accomplished by an analog technique using two RC high-pass filters in series. High-pass refers to high spatial frequencies or short spatial wavelengths passing through the filter, so that low spatial frequencies or long spatial wavelengths, i.e., waviness features, are filtered out of the profile. This technique leads to considerable phase shifts in the transmission of the profile signal and therefore to asymmetrical profile distortions. The influence of such profile distortions on parameters such as *Ra*, *Rq*, and *Rz* may be minimized by the judicious choice of instrument settings. However, for other parameters, particularly those that have come into use more recently, these filter induced distortions are significant and may be unacceptable.

For digital instruments, three types of filters have been used.

(a) The 2RC Filter. This is the traditional analog filter still in use in totally analog instruments. In digital instruments, this filter is well duplicated in digital form for purposes of correlation.

(b) The Phase Correct or PC Filter. This is a filter generated digitally which has the characteristic transmission of the 2RC filter, but which is symmetric in shape so that it eliminates asymmetrical profile distortions. This filter is not defined in Section 9 of this Standard.

(c) The Phase Correct Gaussian Filter. This filter is both symmetric and sharp in its response to eliminate asymmetric distortion and to minimize *crosstalk* between the two components being separated. (An example of *crosstalk* is waviness undulations remaining in the roughness profile after filtering.)

The Gaussian filter has several advantages over the 2RC filter for digital instruments. One major advantage of the use of the Phase Correct Gaussian filter is that the separated roughness and waviness components may be arithmetically added back together to accurately reconstruct the original total profile (i.e., the Gaussian filter can separate the total profile into complementary roughness and waviness profiles, whereas the 2RC filter does not). The complementary nature of roughness and waviness profiles only occurs when $\lambda sw = \lambda c$, which is generally recommended (see para. 1-3.5). The disadvantages of the 2RC filter stem from its lack of sharpness, wherein it allows contributions from shorter-wavelength waviness features into the roughness profile and longer-wavelength roughness features into the waviness profile. This may lead to significant errors in the evaluation of surface parameters.

NONMANDATORY APPENDIX H
REFERENCE SUBROUTINES

H-1 INTRODUCTION

The following subroutines represent examples of computer programming that relates to the parameter definitions of B46.1, Section 1. These implementations are provided for informational purposes only. The programming methodology is based on developing readable implementations for the calculations with clear connections to the B46.1, Section 1 definitions. Thus, the subroutines are not optimized in regard to performance.

As with any published source code, these subroutines should be used with the highest degree of care. Small errors in transcription can have a significant impact on the computed results. Therefore, it is recommended that the user of these subroutines thoroughly test his or her implementation.

H-2 REFERENCE

The following is a list of publications referenced in this Standard.

ANSI X3.159-1989, American National Standard for Information Systems — Programming Language — C

Publisher: The American National Standards Institute (ANSI), 25 West 43rd Street, New York, NY 10036 (www.ansi.org)

H-3 SOURCE CODE

The subroutines are provided as ANSI C functions using standard data types and language constructs.

H-4 SUBROUTINES

Refer to Fig. H-4-1.

Fig. H-4-1 Subroutines

Shared Header File

```
//Algor.h - B46 Reference Algorithms Round Robin
//            Function Prototypes and Defines
//
//     Last Revised: April 20, 1999
#define TRUE 1
#define FALSE 0
#define ROUND(x) (int) ((x)+ 0.5 - (double) ((x)<0.0))

int Ra  (double *array_um, int num, double *ra_um);
int Rq  (double *array_um, int num, double *rq_um);
int Rsk (double *array_um, int num, double *rsk);
int Rku (double *array_um, int num, double *rku);
int Rz  (double *array_um, int num, double cutoff_mm,
         double spacing_mm, double *rz_um, int *cutoffs);
```

Average Roughness, Ra

```
/********************************************************

Ra : Calculates Average Roughness (Ra) on an array
     Assumes that the array has a zero mean. Micrometer
     profile units are assumed, however any profile
     units can be used and the resulting Ra value will
     be of the profile units.

argument(s):
   array_um - A pointer to a double array of um profile values.
              (assumed to have a zero mean)
              Values are unchanged by this function.
   num      – The number of elements in the array.
              Value is unchanged by this function.
calculates:
   *ra_um   – a double precision pointer to the calculated
              Ra value in the units of the array (assumed um).

return: (int)
   TRUE  - Success
   FALSE - Fail

globals: none
```

Fig. H-4-1 Subroutines (Cont'd)

```
*****************************************************/
int Ra (double *array_um, int num, double *ra_um)
{
   int i ;
   double sum ;

   if (num <= 0)
   {
    *ra_um = 0.0 ;
    return FALSE ;
   }
   sum = 0.0 ;
   for (i= 0; i<num; i++)
   {
     if (array_um[i] < 0.0)
        sum -= array_um[i];
     else
        sum += array_um[i] ;
   }
   *ra_um = sum/(double)num ;

   return TRUE ;
} // end Ra
```

RMS Roughness, Rq

```
/*****************************************************
*Rq : Calculates RMS Roughness (Rq) on an array
     Assumes that the array has a zero mean. Micrometer
     profile units are assumed, however any profile
     units can be used and the resulting Rq value will
     be of the profile units.

argument(s):
   array_um - A pointer to a double array of um profile values.
              (assumed to have a zero mean)
              Values are unchanged by this function.
   num      - the number of elements in the array
              Value is unchanged by this function.
calculates:
  *rq_um    - a double precision pointer to the calculated
              Rq value in the units of the array (assumed um).

return: (int)
   TRUE  -  Success
   FALSE -  Fail

globals: none
```

Fig. H-4-1 Subroutines (Cont'd)

```
*****************************************************/
int Rq (double *array_um, int num, double *rq_um)
{
int i ;
double sum ;

if (num <= 0)
{
*rq_um = 0.0 ;
return FALSE ;
}
sum = 0.0 ;
for (i= 0; i<num; i++)
sum += (array_um[i]*array_um[i]);

*rq_um = sqrt(sum/(double)num);
return TRUE ;
} // end Rq
```

Skewness,Rsk

```
/*****************************************************
Rsk : Calculates Skewness (Rsk) on an array
      Assumes that the array has a zero mean.

argument(s):
   array_um  - A pointer to a double array of um profile values.
               (assumed to have a zero mean)
               Values are unchanged by this function.
   num       - the number of elements in the array
               Value is unchanged by this function.
calculates:
   *rsk      - a double precision pointer to the calculated
               Rsk value (dimensionless).

Calls: Rq

return: (int)
   TRUE  -  Success
   FALSE -  Fail

globals: none
```

Fig. H-4-1 Subroutines (Cont'd)

```
*************************************************/
int Rsk (double *array_um, int num, double *rsk)
{
   int i, rq_ok ;
   double sum;
   double rq;

   if (num <= 0)
   {
     *rsk = 0.0 ;
     return FALSE ;
   }

   sum = 0.0;
   for (i= 0; i<num; i++)
      sum += (array_um[i]*array_um[i]*array_um[i]) ;

   rq_ok = Rq(array_um, num, &rq) ;
   if (!rq_ok)
   {
      *rsk = 0.0 ;
      return FALSE ;
   }

*rsk = sum/(rq*rq*rq*num) ;

return TRUE ;

} // end Rsk
```

Kurtosis, Rku

```
/*********************************************************************
Rku : Calculates Rku on an array
      Assumes that the array has a zero mean.

argument(s):
   array_um - A pointer to a double array of um profile values.
              (assumed to have a zero mean)
              Values are unchanged by this function.
   num      - the number of elements in the array
              Value is unchanged by this function.
calculates:
   *rku     - a double precision pointer to the calculated
              Rku value (dimensionless).

Calls: Rq

return: (int)
   TRUE  -  Success
   FALSE -  Fail

globals: none
```

Fig. H-4-1 Subroutines (Cont'd)

```
*****************************************************/
int Rku (double *array_um, int num, double *rku)
{
   int i, rq_ok ;
   double sum ;
   double rq ;

   if (num <= 0)
   {
      *rku = 0.0 ;
      return FALSE ;
   }
   sum = 0.0 ;

   for (i= 0; i<num i++)
      sum += (array_um[i]*array_um[i]*array_um[i]*array_um[i]) ;

   rq_ok = Rq(array_um, num, &rq) ;
   if (!rq_ok)
   {
      *rku = 0.0 ;
      return FALSE ;
   }
   *rku = sum/(rq*rq*rq*rq*num) ;

   return TRUE ;

} // end Rku
```

Average Maximum Height of the Profile, Rz

```
/*****************************************************
Rz : Calculates Rz on an array. Micrometer
     profile units are assumed, however any profile
     units can be used and the resulting Rz value will
     be of the profile units.

argument (s):
   array_um - A pointer to a double array of um profile values.
              (assumed to have a zero mean)
              Values are unchanged by this function.
   num      - the number of elements in the array
              Value is unchanged by this function.
   cutoff_mm- the roughness cutoff length (mm)
              Value is unchanged by this function.
              Millimeter units are assumed, however any units
              can be used as long as the units are the same as
              those used for "spacing_mm".
              NOTE: The cutoff_mm value should be an integer
                    multiple of the sampling interval for this
                    subroutine.
```

Fig. H-4-1 Subroutines (Cont'd)

```
  spacing_mm- the sampling interval (assumed uniform) (mm).
              Value is unchanged by this function.
              Millimeter units are assumed, however any units
              can be used as long as the units are the same as
              those used for "cutoff_mm".
              NOTE: The cutoff_mm value should be an integer
                    multiple of the sampling interval for this
                    subroutine.
calculates:
   *rz_um   - a double precision pointer to the calculated
              Rz value in the units of the array.
   *cutoffs - the number of complete cutoffs found in the array.
return: (int)
   TRUE  -  Success
   FALSE -  Fail

globals: none
**********************************************************************/
int Rz (double *array_um, int num, double cutoff_mm,
        double spacing_mm, double *rz_um, int *cutoffs)
{
   int j, cutoff_ref,
       array_ref, whole_cutoffs,
       points_per_cutoff ;
   double actual_points_per_cutoff,
       peak, valley,
       peak_sum, valley_sum ;
   if (num < = 0)
   {
    *cutoffs = 0 ;
    *rz_um = 0.0 ;
    return FALSE ;
   }

   // compute the double precision (fractional)
   // number of points  per cutoff
   actual_points_per_cutoff = cutoff_mm/spacing_mm ;

   // reduce the number to the lowest whole number of points
   points_per_cutoff= floor(actual_points_per_cutoff);
   // NOTE: The cutoff (cutoff_mm) value should be an integer
   //       multiple of the sampling interval (spacing_um)
   //       for this subroutine.

   // determine the number of whole cutoffs
   // (integer divided by integer)
   whole_cutoffs = num/points_per_cutoff ;
   // need at least one cutoff!
   If (whole_cutoffs < 1)
   {
   *rz_um = 0.0 ;
   return FALSE ;
   }
   // initialize the sums
   peak_sum = 0.0 ;
   valley_sum = 0.0 ;
```

Fig. H-4-1 Subroutines (Cont'd)

```
// start at -1, the loop will increment prior to processing
array_ref = -1 ;

for (cutoff_ref= 0; cutoff_ref<whole_cutoffs; cutoff_ref++)
{
  array_ref++ ;

// set peak and valley at first point
//in this cutoff
  peak = valley = array_um[array_ref] ;

  // use j for the loop, but increment the array_ref
  for (j= 1; j<points_per_cutoff; j++)
  {
    array_ref++ ;
    // modify the peak and valley if a new one is found
    if (array_um[array_ref] > peak)
      peak = array_um[array_ref] ;
    else if (array_um[array_ref] < valley)
      valley = array_um[array_ref] ;
    }
    peak_sum += peak ;
    valley_sum += valley ;
  }
  *rz_um =  (peak_sum - valley_sum)/(double)whole_cutoffs ;
  *cutoffs = whole_cutoffs ;

  return TRUE ;
  } // end Rz
```

NONMANDATORY APPENDIX I
A COMPARISON OF ASME AND ISO SURFACE TEXTURE PARAMETERS

The following table is a summary of the various ASME B46.1-2009 roughness/waviness parameters as they relate to ISO 4287-1997 parameters. When an ASME B46.1-2009 parameter is identical to an ISO 4287-1997 parameter, the entries appear juxtaposed in the table. When an ASME B46.1-2009 parameter is similar but not identical to an ISO 4287-1997 parameter, the entries appear in different rows. In many cases, the parameters are similar in principle, but differ based on whether the evaluation length or sampling length is used for the calculation.

The ISO 4287-1997 Standard uses the "*P*" symbol to designate parameters related to the unfiltered profile, the "*R*" symbol to designate filtered roughness parameters, and the "*W*" symbol to designate filtered waviness parameters. The ASME B46.1-2009 Standard is primarily concerned with roughness parameters as designated by the "*R*" symbol and additional terms as defined. ASME B46.1-2009 also references one waviness parameter, *Wt*.

Table I-1 ASME B46.1-2009 Parameters

ASME B46.1-2009 Parameter	Length Defined Over	ISO 4287-1997 Parameter	Length Defined Over
Traversing length	. . .	. . .	. . .
Evaluation length, *L*	. . .	Evaluation length, *ln*	. . .
Roughness sampling length, *lr*	. . .	Sampling length, *lr*	. . .
Waviness sampling length, *lw*	. . .	Sampling length, *lw*	. . .
Roughness long-wavelength cutoff, λc	. . .	profile filter, λc	. . .
Roughness short-wavelength cutoff, λs	. . .	profile filter, λs	
Waviness long-wavelength cutoff, λcw	. . .	profile filter, λf	. . .
Waviness short-wavelength cutoff, λsw	. . .		
Profile peak	. . .	Profile peak	. . .
Profile valley	. . .	Profile valley	. . .
Profile irregularity	. . .	Profile element	. . .
Profile height function, $Z(x)$	. . .	Ordinate value, $Z(X)$	. . .
Roughness average, *Ra* (*AA*, *CLA*)	Evaluation	Arithmetical mean deviation of the assessed profile, *Ra*	Sampling
Root mean square roughness, *Rq*(*rms*)	Evaluation	Root mean square deviation of the assessed profile, *Rq*	Sampling
Maximum profile peak height, *Rp*	Evaluation	. . .	. . .
Maximum profile valley depth, *Rv*	Evaluation	Maximum profile valley depth, *Rv* [Note (1)]	Sampling
Maximum height of the profile, *Rt*	Evaluation	Total height of profile, *Rt*	Evaluation
Distance between the highest point of the profile and mean line, *Rpi*	Sampling	Maximum profile peak height, *Rp*	Sampling
Average maximum profile peak height, *Rpm*	Evaluation	. . .	. . .
Vertical distance between the highest and lowest points of the profile, *Rti*	Sampling	Maximum height of the profile, *Rz* [Note (2)]	Sampling
Average maximum height of the profile, *Rz*	Evaluation	. . .	. . .
Maximum roughness depth, *Rmax*	Evaluation	. . .	. . .
Waviness height, *Wt*	Evaluation	Total height of profile, *Wt*	Evaluation
Mean spacing of profile irregularities, *RSm* [Notes (3) & (4)]	Evaluation	Mean width of profile elements, *RSm* [Note (3)]	Sampling
SAE peak, peak count level, peak density, *Pc*	Evaluation	. . .	. . .
Amplitude density function, ADF(z)	Evaluation	Profile height amplitude curve	Evaluation
Profile bearing length at a specified level, *p*	Evaluation	Material length of the profile, *Ml*(*c*), at a given level, *c*	Evaluation
Profile bearing length ratio, *tp*, at a given level, *p*	Evaluation	Material ratio of the profile, *Rmr*(*c*), at a given level, *c*	Evaluation
Bearing area curve, BAC	Evaluation	Material ratio curve of the profile	Evaluation
Difference in the heights for two profile bearing length ratios *tp*, *Htp*	Evaluation	Profile section height difference, $R\delta c$	Evaluation
Skewness, *Rsk*	Evaluation	Skewness of the assessed profile, *Rsk*	Sampling
Kurtosis, *Rku*	Evaluation	Kurtosis of the assessed profile, *Rku*	Sampling
Power spectral density, PSD(f)	Evaluation	. . .	. . .
Autocovariance function, ACV(τ)	Evaluation	. . .	. . .
Autocorrelation function, ACF(τ)	Evaluation	. . .	
Correlation length	Evaluation	. . .	. . .
Average absolute slope, $R\Delta a$	Evaluation	. . .	. . .
Root mean square slope, $R\Delta q$	Evaluation	Root mean squared slope of assessed profile, $R\Delta q$	Sampling

GENERAL NOTES:

(a) All ASME B46.1-2009 area profiling parameters have no counterpart in the ISO 4287-1997.

(b) ASME B46.1-2009 parameters are defined and calculated over the evaluation length. In contrast, ISO parameters defined over the sampling length, in accordance with ISO 4287-1997, are calculated over the evaluation length, in accordance with ISO 4288-1996, which states, "an average parameter estimate is calculated by taking the arithmetic mean of the parameter estimates from all of the individual sampling lengths."

NOTES:

(1) In ISO 4287-1984, maximum profile valley depth, *Rm*.

(2) In ISO 4287-1984, maximum height profile, *Ry*.

(3) Height and spacing discrimination are applied to the counting of profile elements.

(4) Counting of the irregularities based on each crossing of the mean line without height and spacing discrimination was called *Sm* in ASME B46.1-1995 and earlier editions.

NONMANDATORY APPENDIX J
FUNCTIONAL STANDARDS

In order to promote the technology of surface texture measurement and increase the awareness of its applications, a listing of industry standards which specify roughness and waviness values is provided in Table J-1. Table J-1 is simply a compilation of standards documents that contain some reference to surface texture specifications. The particular measurement conditions, parameters, and values are only included as reference summary information. Those interested should consult the cited reference document for the specification details. Suggestions for additional references are encouraged and should be made to the ASME B46 Committee Project Team 32. ASME assumes no liability for the accuracy of these references and in no way confirms or endorses the specification values indicated in these standards.

Table J-1 Reference Standards

Standard	Title	Issuing Organization	Section/ Paragraph Cited
RMA OS-1-1	Shaft Finish Requirements for Radial Lip Seals	Rubber Manufacturers Assoc. (RMA)	5.0
Comments: *Recommended Roughness Values for Shafts Using Radial Lip Seals*. The Rubber Manufacturers Association (RMA) has published standard OS.1.1. This standard is available through *www.rma.org*. A significant aspect of this standard is to specify use of a Gaussian filter cutoff value of $\lambda c = 0.25$ mm. This filter setting focuses on shorter peak spacing features that are active on the scale of radial lip seal contact widths.			
ASME B16.5	Pipe Flanges	The American Society of Mechanical Engineers (ASME)	6.4.4
Comments: *Pipe Flange Facing Finish*. The finish of contact faces of pipe flanges and connections is specified in ASME B16.5, para. 6.4.4. This Standard indicates that finishes shall be judged by visual comparison with roughness standards and not by instruments having stylus tracers and electronic amplification.			
ASTM F 37	Sealability of Gasket Materials	American Society for Testing and Materials (ASTM)	5.2.4
Comments: *Surface Finish in Gasket Sealability Testing*. The roughness of test platens for (sheet) gasket sealability (leak rate at load) testing is described in standard ASTM F 37 Sealability of Gasket Materials, para. 5.2.4. This specification gives a range of roughness values in units of "μin. RMS." It has been suggested that this be revised to the more current common parameter Ra, since use of RMS values has been discontinued and is not the same as the Rq or true RMS roughness height value.			
ASTM F 2033-05	Total Hip Joint Prosthesis Bearing Surfaces	American Society for Testing and Materials (ASTM)	3.1.3, 3.2, 3.3
Comments: *Standard Specification for Total Hip Joint Prosthesis and Hip Endoprosthesis Bearing Surfaces Made of Metallic, Ceramic, and Polymeric Materials*. The roughness of hip joint prosthesis components are measured using a cutoff length $\lambda c = 0.8$ mm. Femoral head roughness 0.05 μm Ra max. at pole and 30-deg angle locations. Acetabular component roughness is 2 μm Ra max. for polymeric materials and 0.05 μm Ra max. for metallic and ceramic materials. Hip endoprosthesis surfaces are 0.5 μm Ra max.			
ASTM D 7127-05	Abrasive Blast Cleaned Metal Surfaces	American Society for Testing and Materials (ASTM)	1.1, 6.1
Comments: *Measurement of Surface Roughness of Abrasive Blast Cleaned Metal Surfaces Using a Portable Stylus Instrument*. The roughness characteristics of abrasive blast cleaned metal surfaces can be evaluated using roughness parameters Rt, Rmax, Rz, and Pc. These should only be applied for surfaces with an Rmax value between 10 μm and 150 μm and with a Pc value less than 180 peaks/cm. A stylus tip radius of 2μm or 5 μm may be used. All parameter values are reported at five locations and include the average parameter value.			
SAE J911-1998	Cold Rolled Sheet Steel	Society of Automotive Engineers (SAE)	All
Comments: *Surface Texture Measurement of Cold Rolled Sheet Steel*. The roughness characteristics of cold rolled sheet steel surfaces can be evaluated using roughness parameters Roughness Average (Ra) and Peak Density (Pc). The Peak Count Level is an important measurement setting for determination of Peak Density. Peak Count Level is defined as the vertical distance between upper and lower boundary limits that are equidistant from the roughness mean line. A value of 1.25 μm is specified for Peak Count Level. All parameter values are reported as an average of 10 measurements – 5 in longitudinal and 5 in transverse directions.			

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