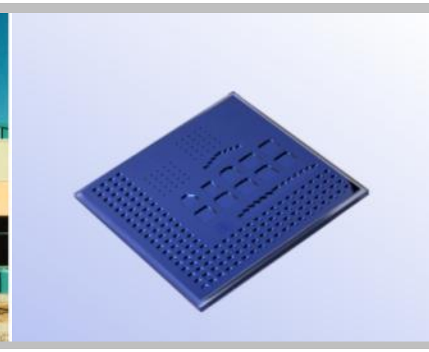
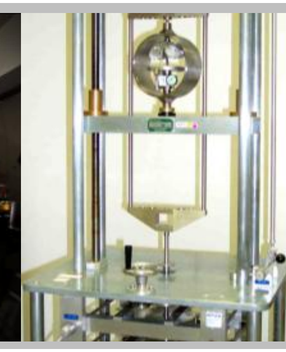
Exceptional service in the national interest

SAND2016-4434PE





Measuring and Characterizing Surface Topography

Hy D. Tran, PhD, PE

Senior Scientist, Sandia National Laboratories

AVS short course, May 26, 2016

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Why surface topography?

Surfaces cover everything—and they influence behavior and performance of parts. In this tutorial, we will focus on the topography of surfaces—the texture and roughness. Texture includes both short spatial wavelength components (what one would call roughness) and longer wavelength components (what one would call waviness and form). Texture may have directionality (lay). These qualities are specified in mechanical product drawings, and the evaluation of roughness is defined in both ASME and ISO standards. This tutorial provides an introduction to surface metrology and to the evaluation of roughness. As an outcome, you will understand the fundamentals of surface metrology, including vocabulary, definitions, drawing symbols, evaluation methods, and both contact and non-contact equipment used in measuring surface topography.

This tutorial combines materials developed and presented by various members of the ASME B46 committee on surface texture in various venues. Major acknowledgments to Ted Vorburger, guest scientist at NIST, formerly chair of B46 and currently chair of optical methods working group for ISO 25718; Chris Brown, professor of mechanical engineering at WPI, currently chair of B46; Don Cohen, Michigan Metrology; John Kozar, Ford Motor, and a cast of dozens. Apologies to others whose names were left off the print copy.

Desired outcomes for attendees

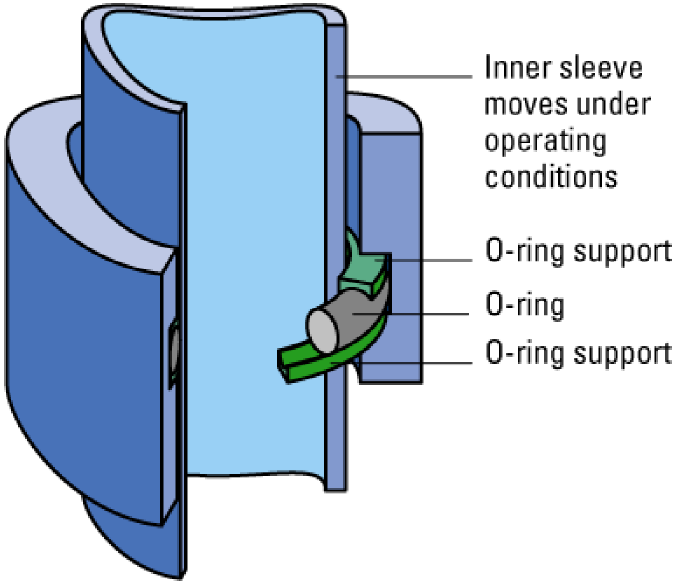
- Describe surface topography, surface metrology, and surface finish
- Describe effects of topography on performance
- Understand symbols used in mechanical drawings on surface finish
- Find major national and international standards used in specifying surface finish
- Describe different parameters used in evaluation of surface texture
- Understand different methods used in measuring surface topography, and the resulting evaluation of surface texture
- Obtain resources for deeper understanding of surface texture and measuring surface texture

Outline:

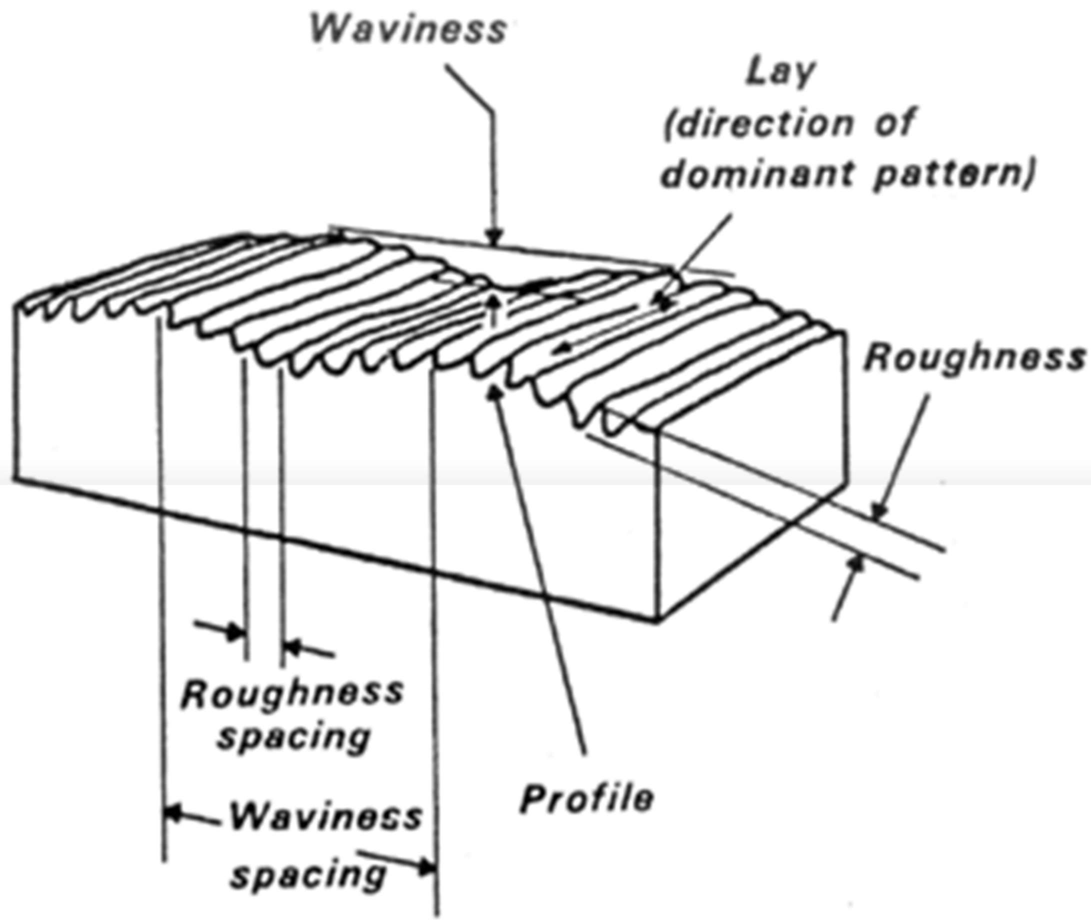
- Surfaces/surface topography—general ideas
- Some discussion about manufacturing methods (mainly machining) and effects on surfaces
- Types of methods for measuring topography (contact, non-contact)
- Surface metrology parameters
- Documentary standards (ASME, ISO)

Why do we care about surface topography?

- Surface texture and topography affect:
  - Wear and friction (sliding surfaces)
  - Electrical and thermal conductivity (contacts)
  - Corrosion properties
  - Fatigue (stress concentrators on surface)
  - Cost (excess cost to make a surface better than it needs to be, or costs due to poor product quality because surface properties were inadequately manufactured or specified)
  - Measurement (especially form: More difficult to meet a tight form requirement if you have too much topography)
  - O-ring seals (be careful if you specify too good a surface finish! Some seal designs actually require that your roughness is in a range between a minimum and maximum value!)
  - etc.

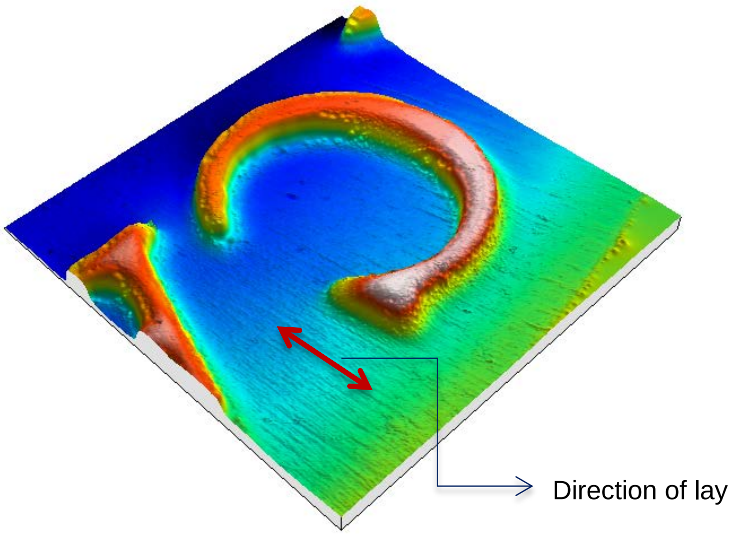


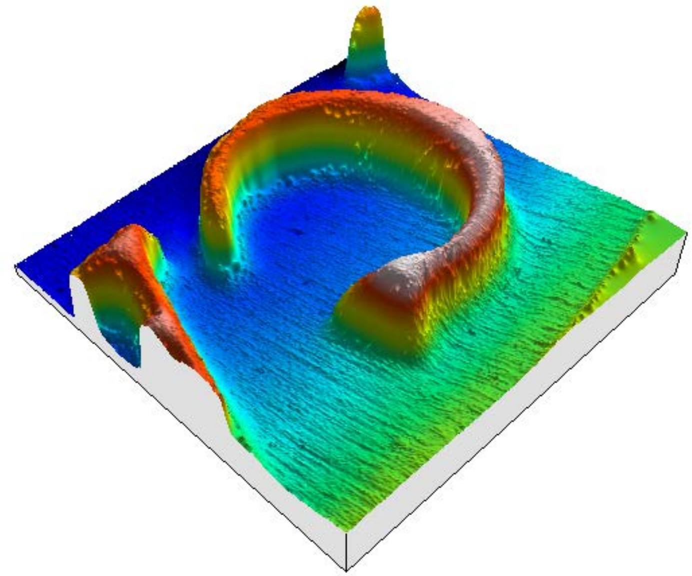
Surface texture terminology

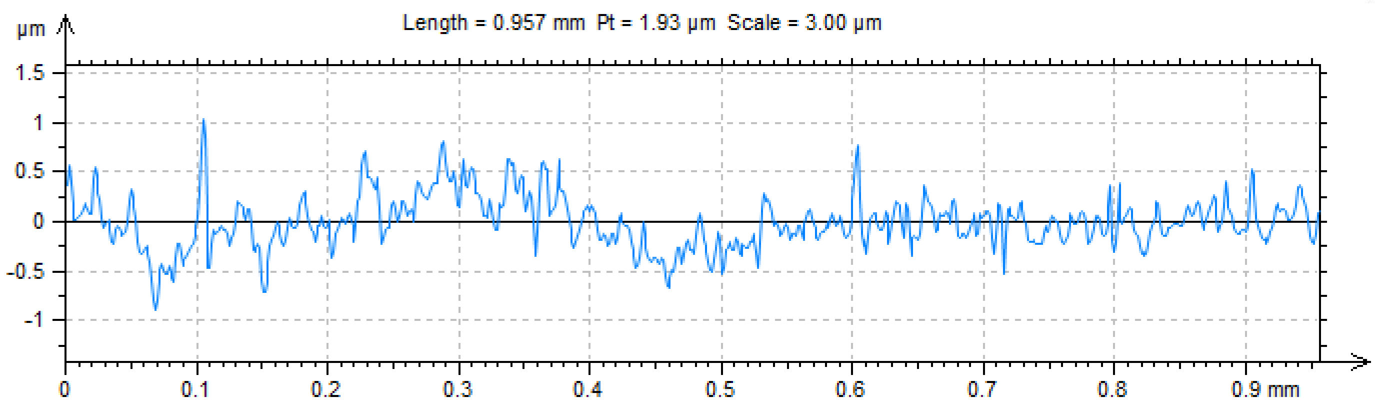


Adapted from ASME B46.1:2009

Beware scale mismatch in visualizing topography







This line, scaled down to 4 mm length, would have Ra ≈ 3 μm (120 μin)

Surface topography: Roughness?

- Topography (will be in next edition of ISO 25718 Part 600)
  - "points in space" defining the boundary between a material (typically a solid material, such as a metal part) and a different material (typically, air) (my definition, not ISO's!)
- Roughness is one element of topography
  - ASME B46 committee: Texture, roughness, waviness, and lay
- Topography (and roughness) have influence on performance:

  - Light scattering vs reflection
  - Resistance to fluid flow
  - Nucleation for boiling
  - Friction, wear
  - Retention of lubricant
  - Stress concentrators (fatigue)
  - Adhesion (paint, coatings, etc.)
  - Thermal conductivity at interface
  - Electrical conductivity at interface
  - Biocompatibility (e.g. osseointegration)
  - etc

In different domains, different terms

Mechanical Engineering	***Optics***	***Semiconductor Technology***
Roughness	Finish	Microroughness
Waviness	Mid-wavelength Slope Error	Orange Peel
Error of Form	Figure	Flatness
Flaws, Imperfections	Imperfections, Digs & Scratches	Defects, Scratches, Pits Other terms

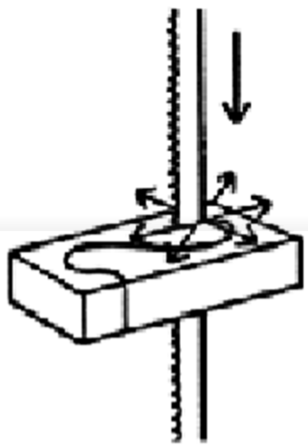
Roughness & mechanical

- Part of the geometrical specification
- Manufacturing never hits the “nominal design specification”
- Always have a manufacturing tolerance
  - Tolerance: Allowable deviation from the nominal value, where your product is still considered “in specification” (my words, not ASME Y14.5)
  - Ideally: Not only “in specification”, but performance also is as expected. Example: Filling an automobile with gasoline; there is an allowable tolerance on the volume delivered (legal specifications in the US through NIST handbooks and propagated to the States)
    - Too much gasoline: Lose $
    - Too little gasoline: Get sued, and lose $
- Texture affects nominal geometry
- Some designers use texture as a proxy for workmanship

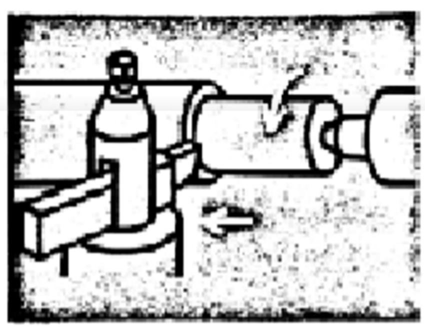
How is roughness generated?

- Various machining operations, in the process of removing material, leave a textured surface

Sawing



Turning

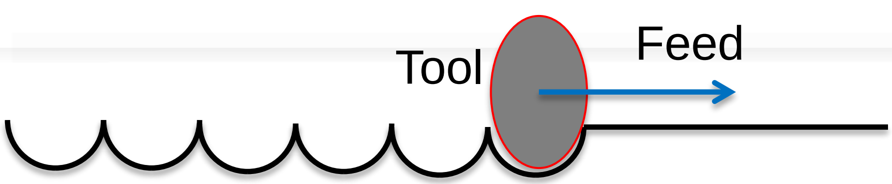


Milling

Grinding

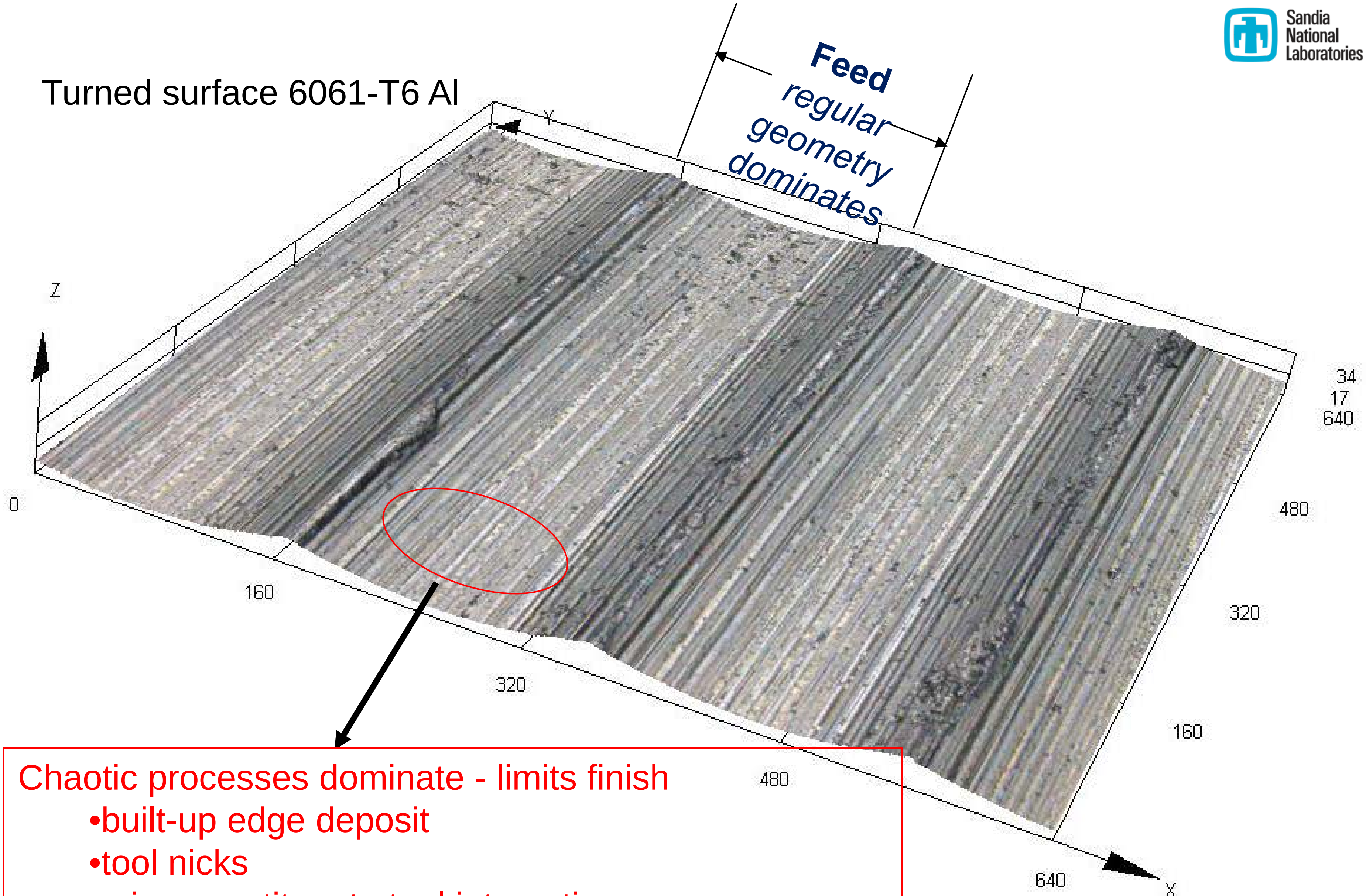
Surface Grinding

Cylindrical Grinding



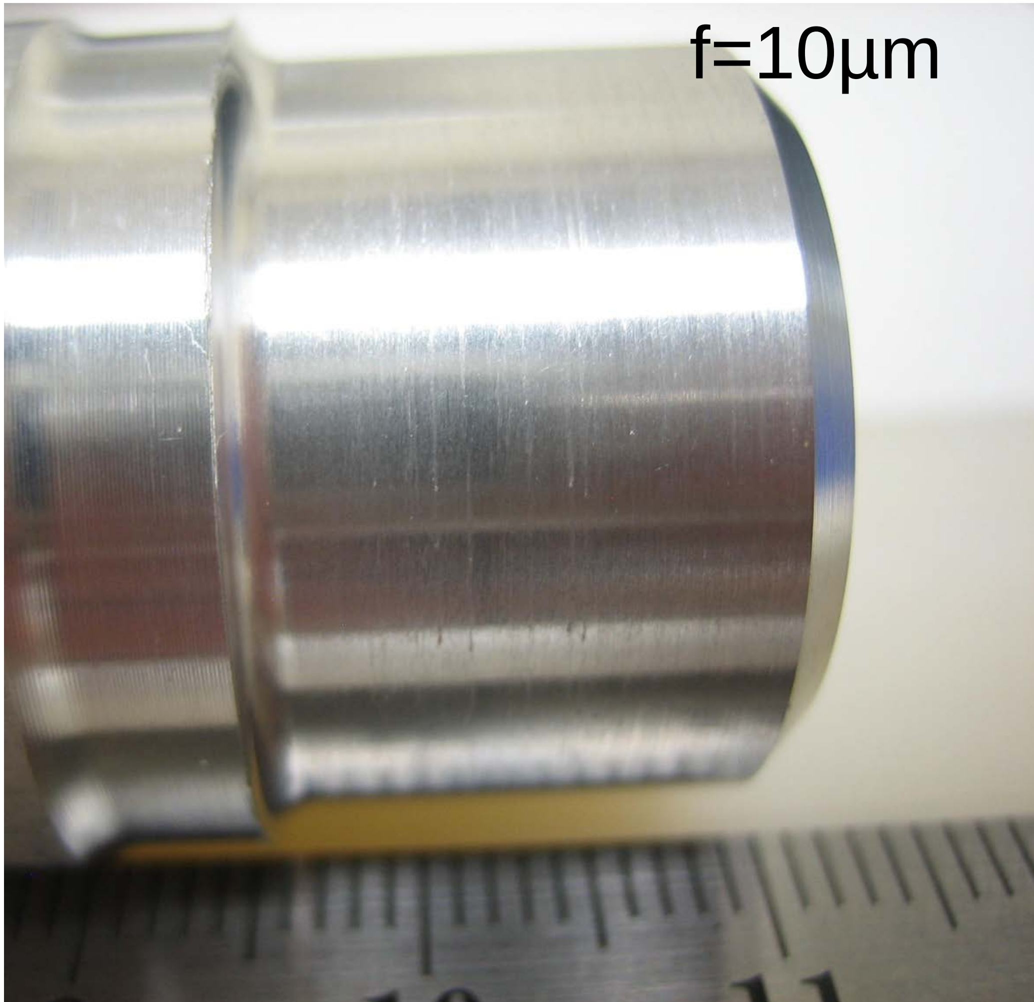
Machine Tools/America's Muscle, National Machine Tool Builder's Association, McLean, VA

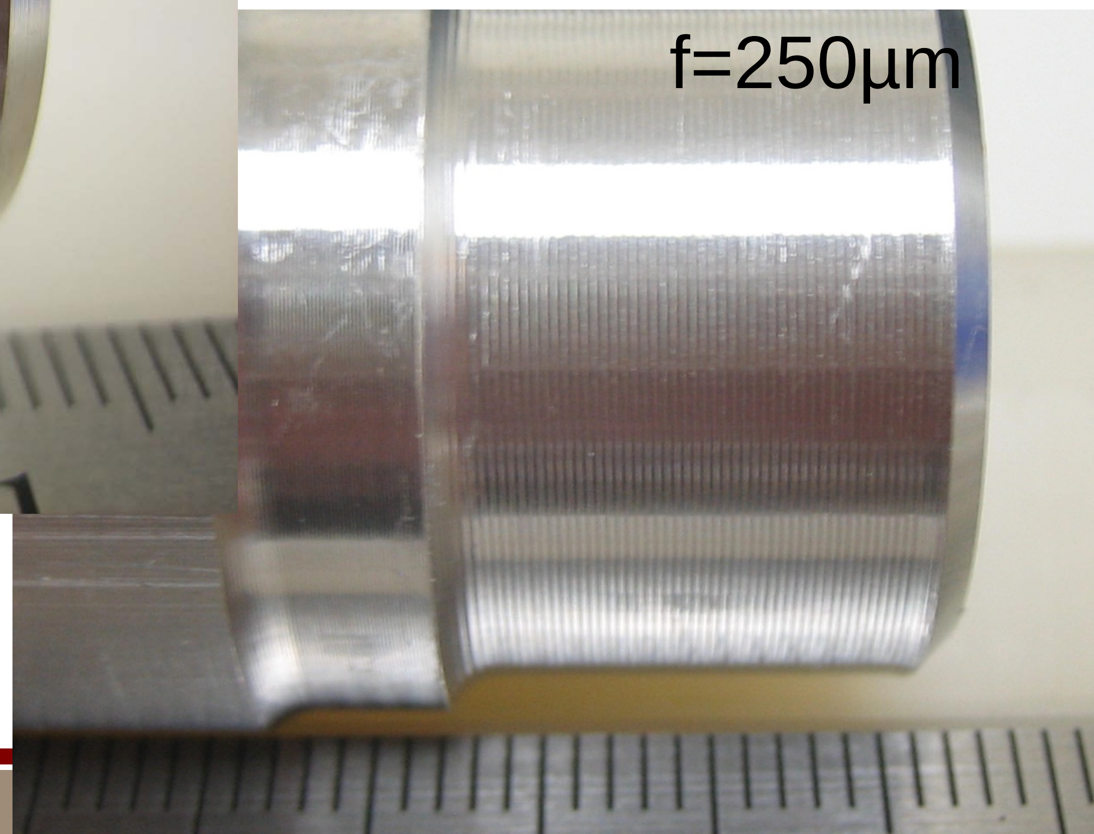
Turned surface 6061-T6 Al



Chaotic processes dominate - limits finish

- built-up edge deposit
- tool nicks
- microconstituents-tool interaction
- micro burrs


f=10µm

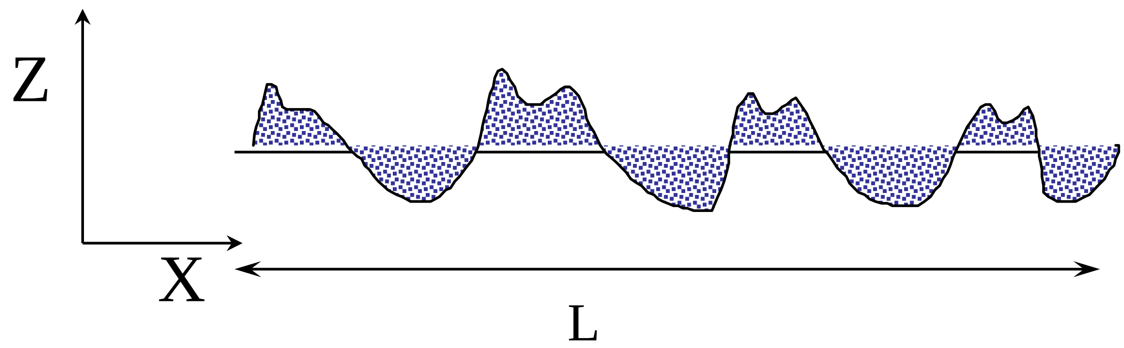

f=250µm

Roughness average (R_a) is a parameter

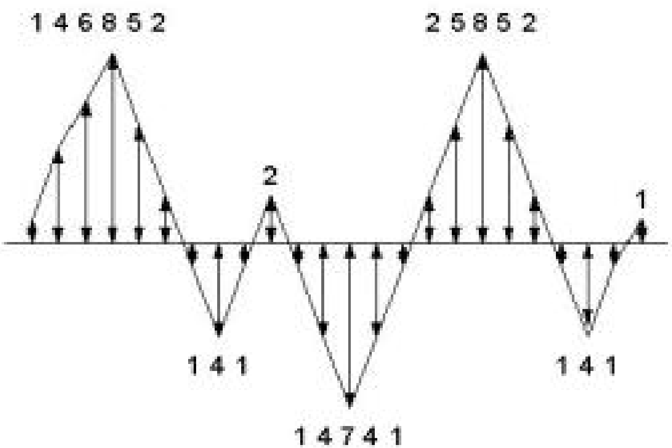
Sandia National Laboratories

- R_a (Roughness Average) is the average deviation of a profile from the mean line.

$$R_a = \frac{1}{L}\int_0^L |Z(x)|\,dx$$



$$R_a = \frac{\sum_{i=1}^{i=n} |Z_i|}{L}$$



Ra = Average(1, 4, 6, 8, 5, 2, 1, 4, 1, 2, 1, 4, 7, 4, 1, 2, 5, 8, 2, 1, 4, 1, 1)

Ra = 3.26

Machining process typical capability:

Typical Methods of Surface Production

Method	Roughness Average Range (µm)
Sawing	0.8 - 50
Milling	0.4 - 12
Turning	0.1 - 12
Diamond Turning	0.001 - 0.05
Grinding	0.001 - 3.2
Polishing	0.0001 - 0.8

Micrographs of Surfaces

The following five plates are taken from J.M. Bennett and L. Mattsson, *Introduction to Surface Roughness and Scattering* (Optical Society of America, Washington, DC, 1989).

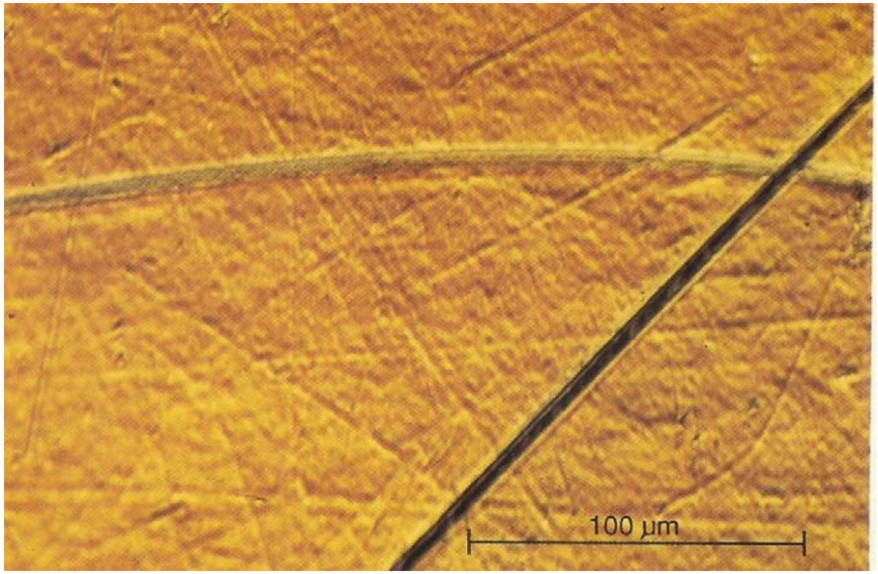


Plate 1. Nomarski micrograph of the surface of a hard contact lens showing isolated large scratches on a background of small scratches.

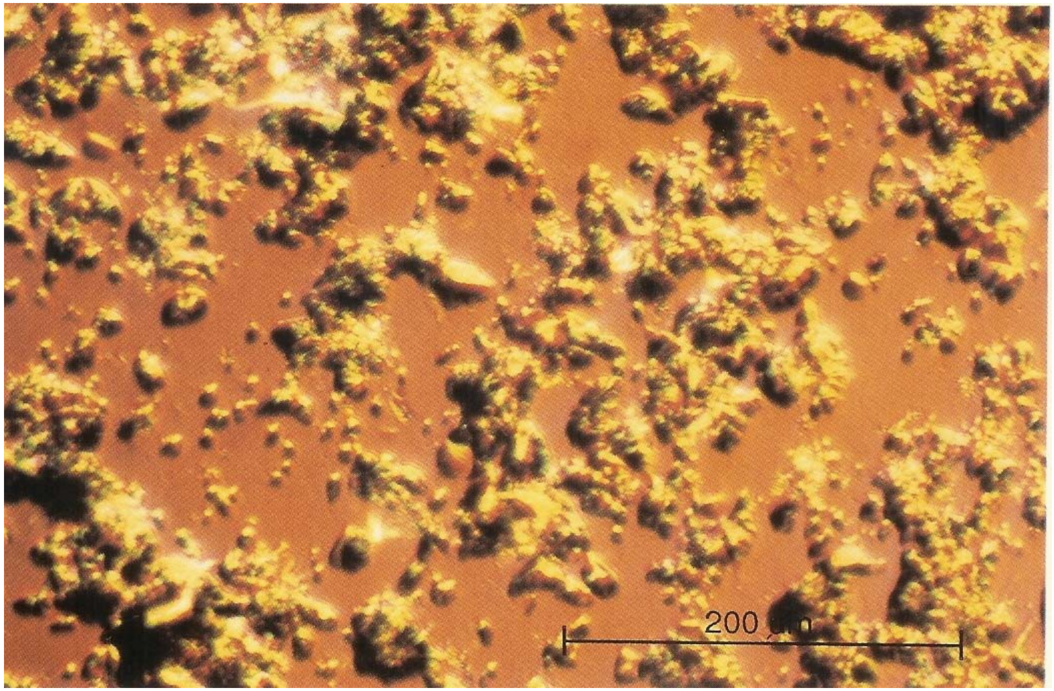


Plate 2. Nomarski micrograph of a partially polished glass surface showing the polished region and pits remaining from the grinding process.

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

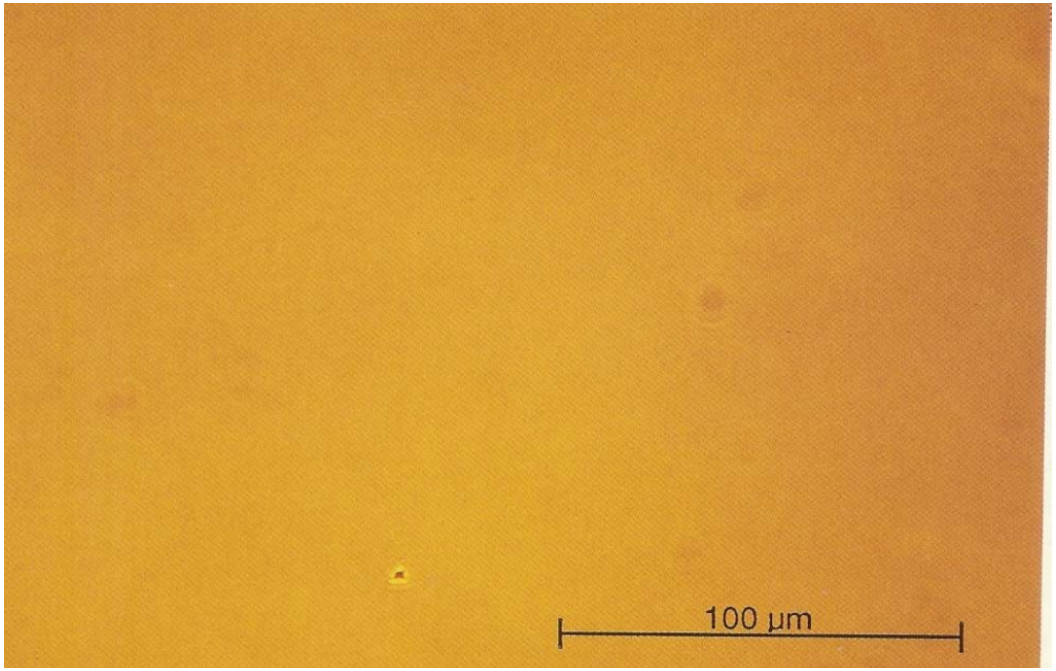


Plate 3. Nomarski micrograph of a well-polished silicon-wafer surface. No microstructures can be seen.

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

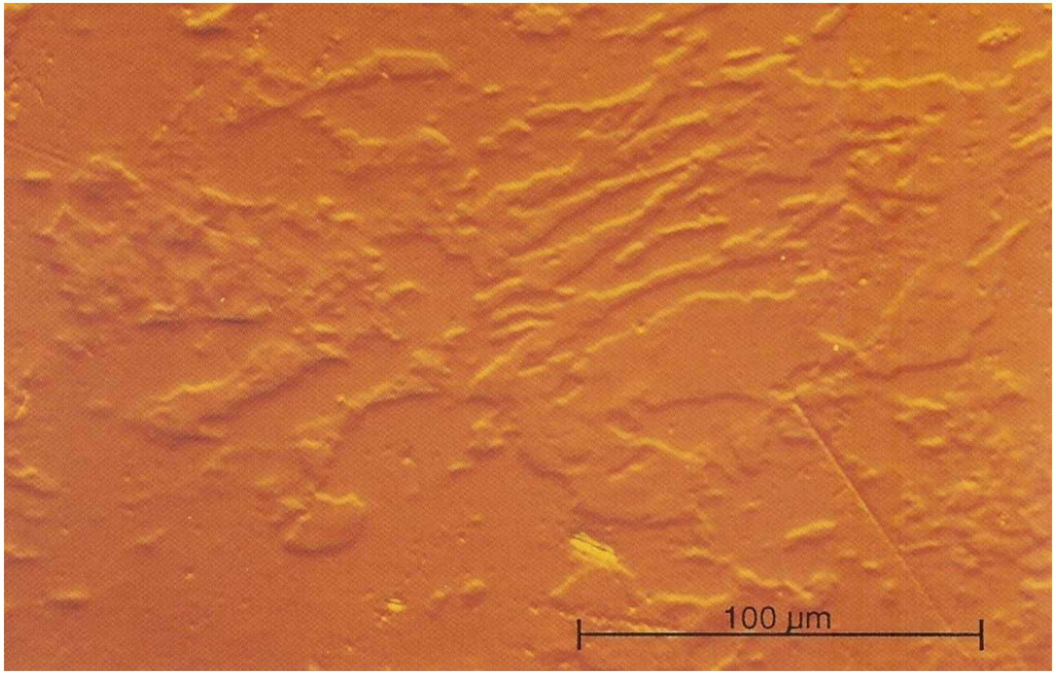
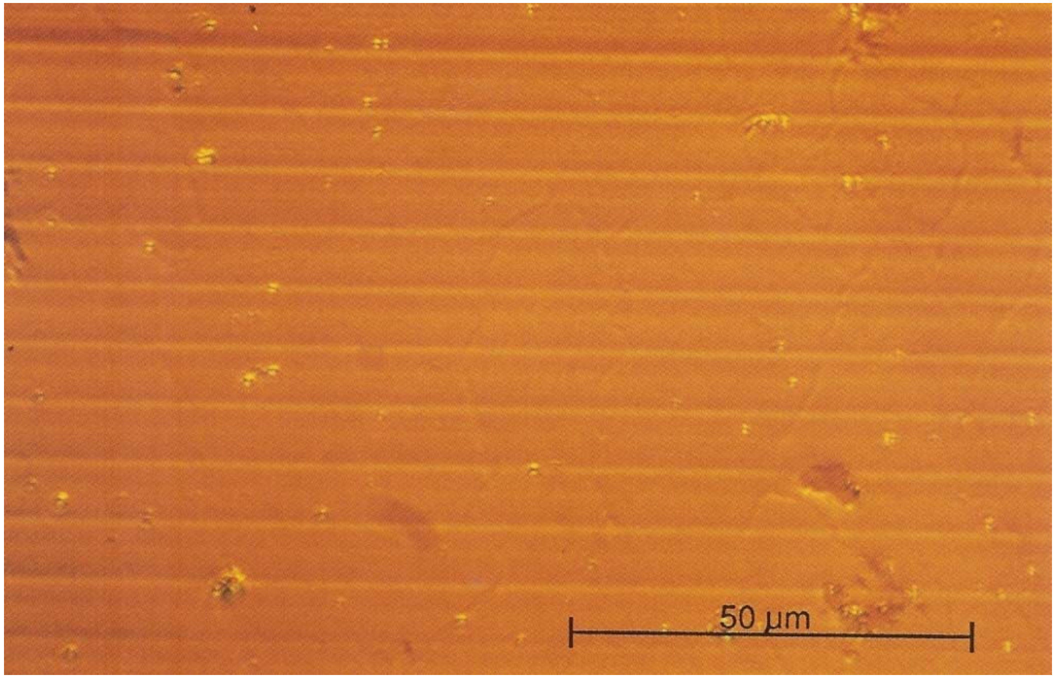


Plate 5. Nomarski micrograph of a well-polished molybdenum surface showing the texture produced by the grains in the material.

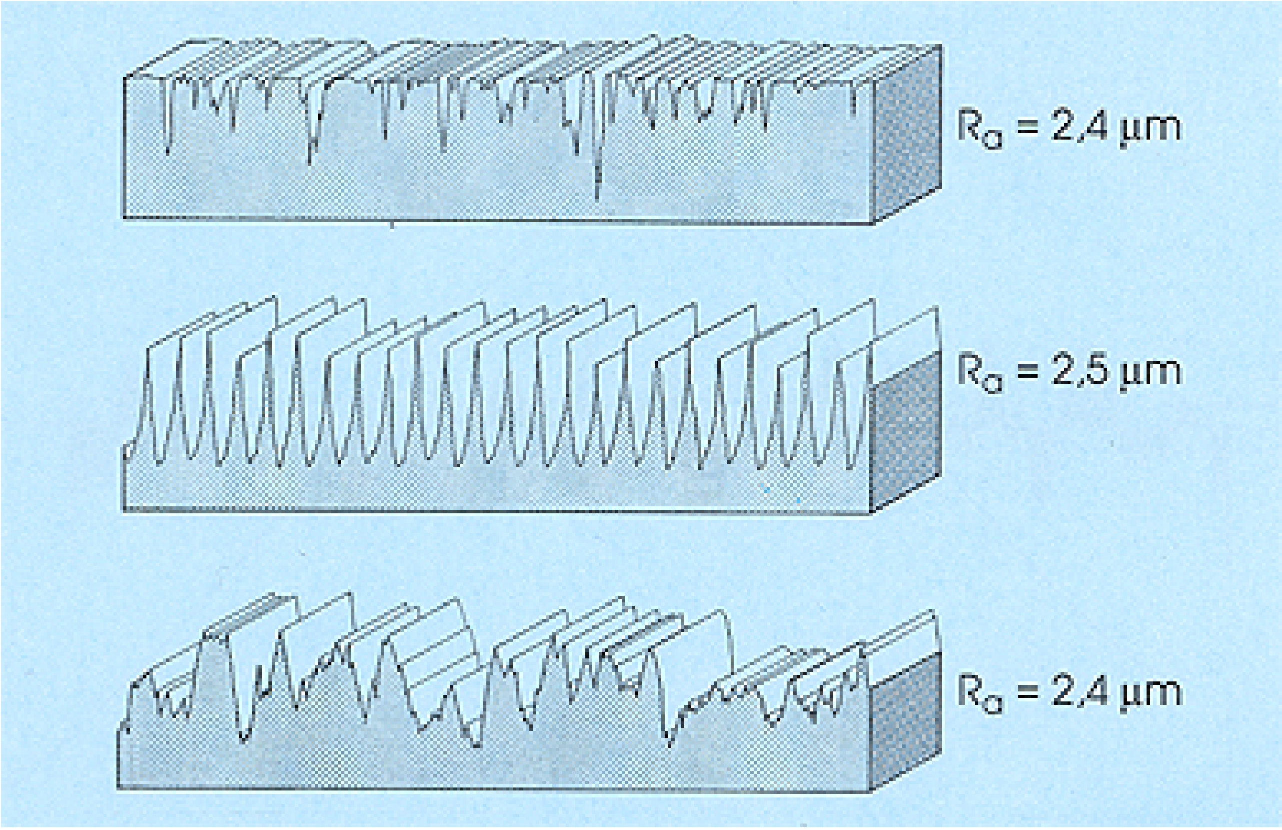
J.M. Bennett and L. Mattsson, *Introduction to Surface Roughness and Scattering* (Optical Society of America, Washington, DC, 1989).

Nomarski Micrograph of a Diamond-turned Aluminum Alloy



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

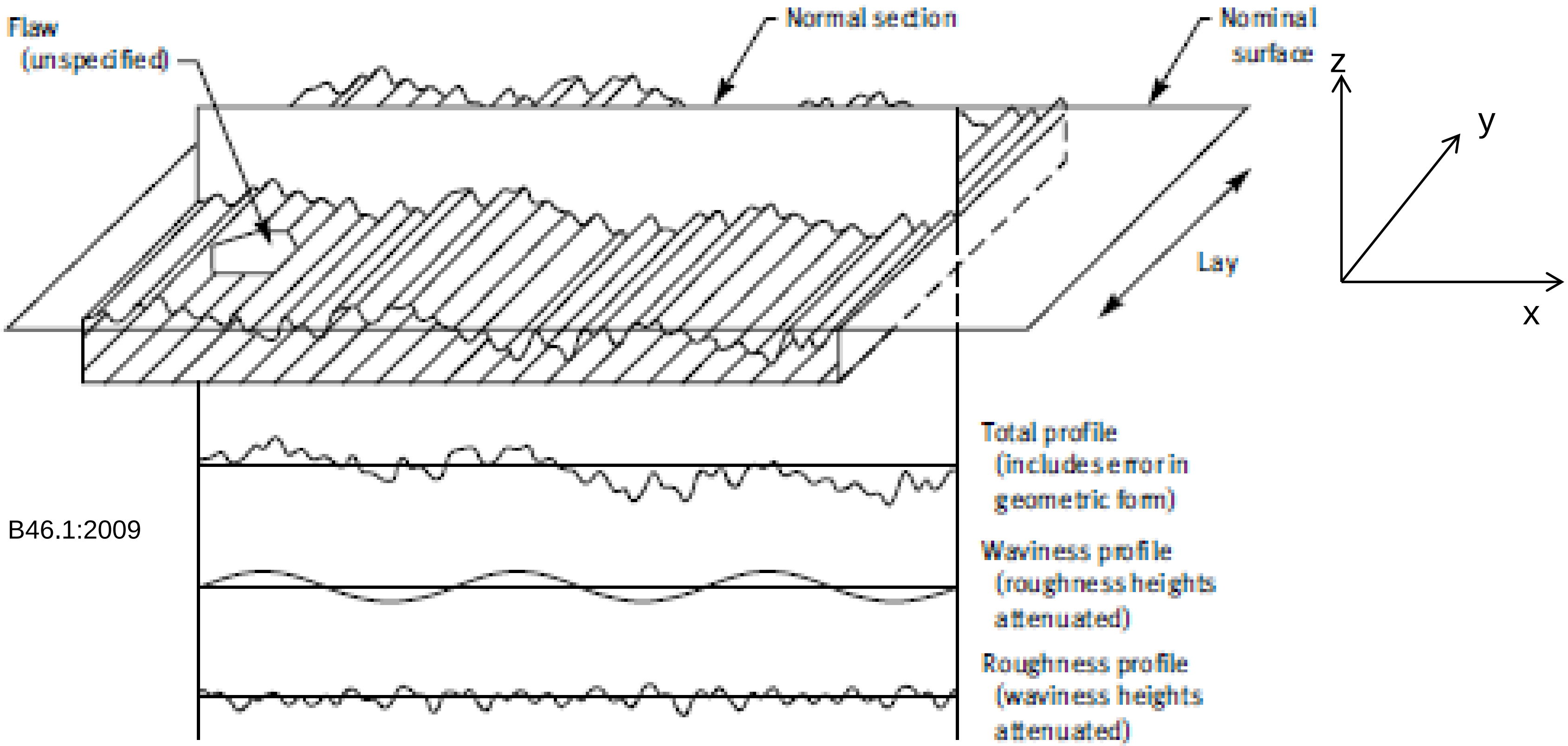
Why R_a Is Not Enough
Similar R_a – Different Surfaces



L. Monk, J. Kozar, M. Habel, *Specifying Surface Finish*,
Ford Motor Company Surface Finish Training Week Oct. 2014

Parameters

Reducing millions and millions of points to a single number



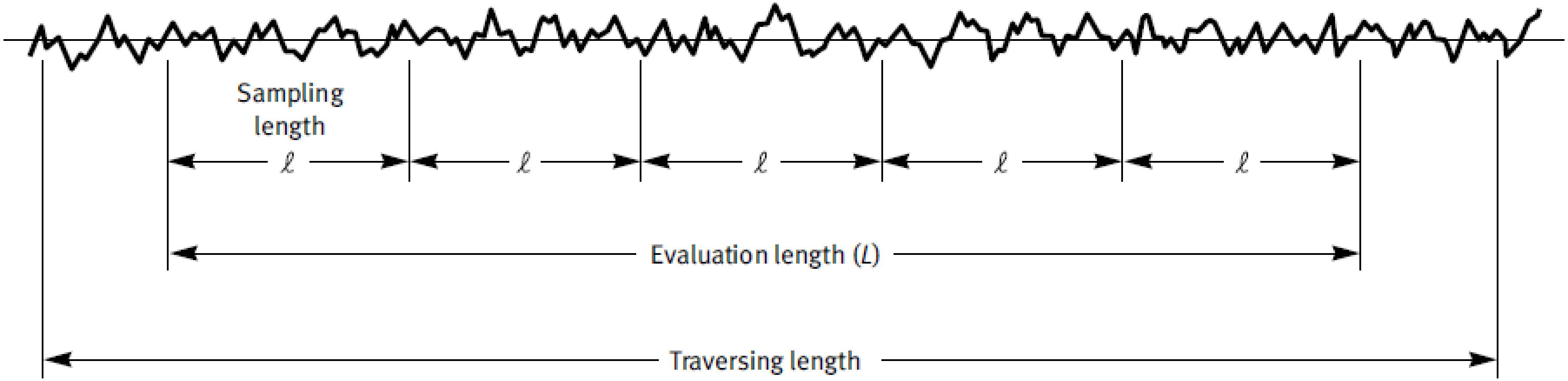
From ASME B46.1:2009

- Surface topography is measured, then, a profile is extracted
- Roughness profile is extracted from total profile
- Parameter is calculated

Parameters for the parameters

- Ra (and other parameters) are defined over a length “L”
- Other parameters for calculation are generally prescribed (for example, how to filter to separate profile from waviness, etc.)

Fig. 1-7 Surface Profile Measurement Lengths



Key Limitations for Profiling Instruments (and for Measurements With Profiling Instruments)

Spatial (Lateral) Resolution

Shortest spatial wavelength (finest spacings) that can be assessed with the instrument.

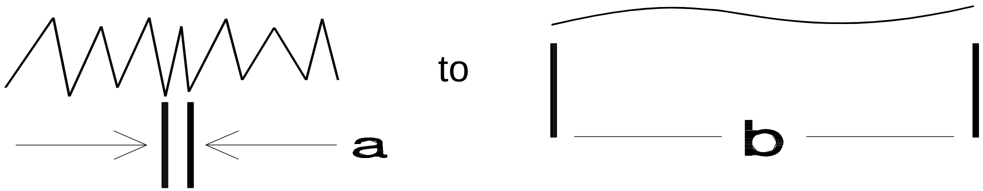
Lateral Range (example: Traversing Length)

Determines the longest spatial wavelengths that can be assessed with the instrument.

Bandwidth Limits

Spatial resolution and longest measurable spatial wavelength,

i.e., from to



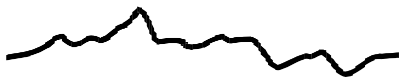
Vertical Resolution

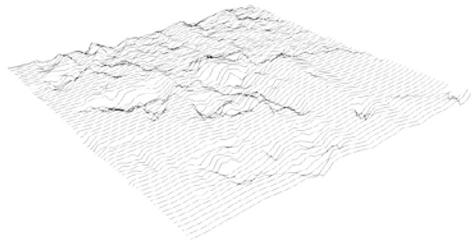
The smallest height variations that can be assessed with the instrument.

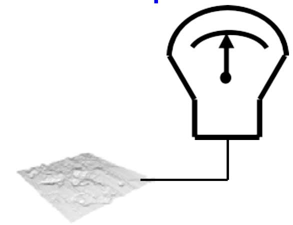
Vertical Range

It is important to know the factors in each instrument (or measurement) that cause these limitations.

A classification of surface texture measurement methods with examples







Line Profiling,
Senses *Z*(*X*)

Contact Stylus Scanning,
Phase Shifting Interferometry,
Circular Interferometric Profiling**,
Optical Differential Profiling

Areal Topography,*
Senses *Z*(*X*,*Y*) or
Z(*X*) as a function of *Y*

Contact Stylus Scanning,
Phase Shifting Interferometry,
Coherence Scanning Interferometry,
Confocal Microscopy,
Confocal Chromatic Microscopy,
Structured Light Projection,
Focus Variation Microscopy,
Point Autofocus Profiling,
Photometric Stereo,
Digital Holography Microscopy,
Optical Differential Profiling,
Angle Resolved SEM,
SEM Stereoscopy,
Scanning Tunneling Microscopy,
Atomic Force Microscopy,

Area-Integrating

Total Integrated Scatter,
Angle Resolved Scatter,
Parallel Plate Capacitance, Pneumatic

*The accuracy of Z(Y) profiling depends on the method and should be ascertained for each method.

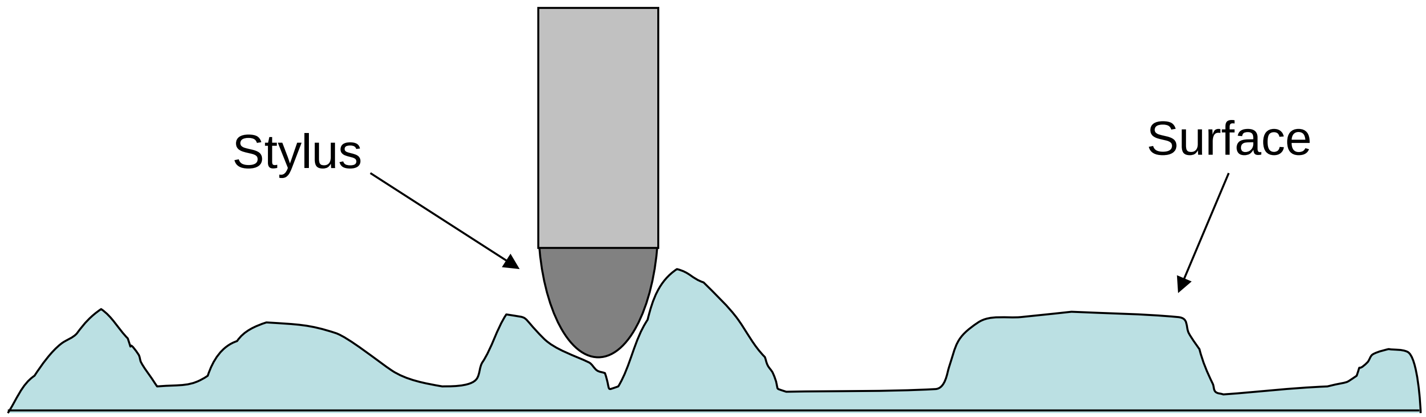
**This technique relies on circular scanning to produce a Z(θ) profile.

Refs:
T.V. Vorburger et al., Int. J. Adv. Manuf. Technol. **33**, 110 (2007);

ISO Standard 25178-6 (2010), *Classification of Methods for Measuring Surface Texture.*

Micro-Roughness

- The radius of the stylus tip for stylus instruments acts as a low-pass filter
- Optical instruments do not filter out micro-roughness automatically since they are non-contact, but Sparrow limit acts as a micro-roughness filter

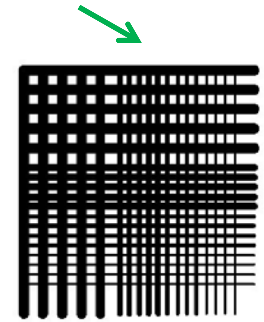


Lateral Period Limit
Seen on an optical instrument

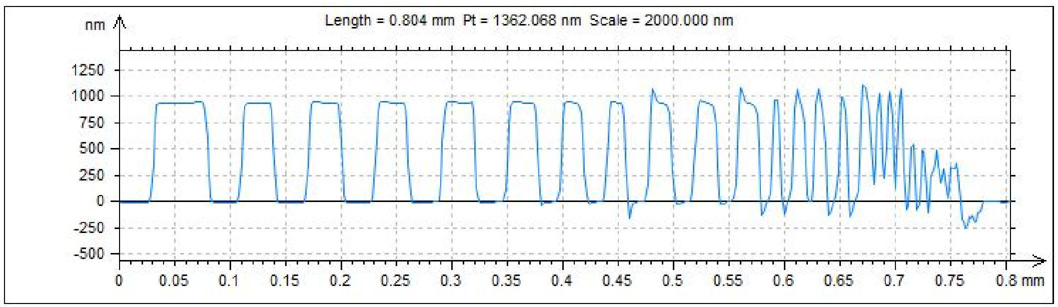
Sandia National Laboratories

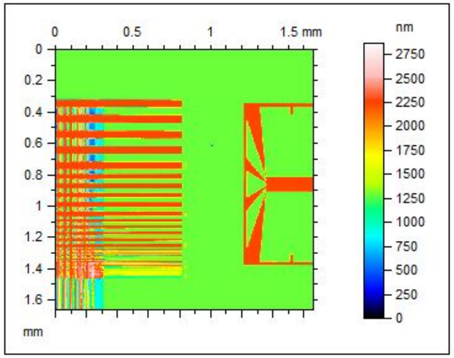
- The spatial or lateral resolution of a surface topography measuring instrument and its ability to distinguish and measure closely spaced surface features

Incremental Pitch Area

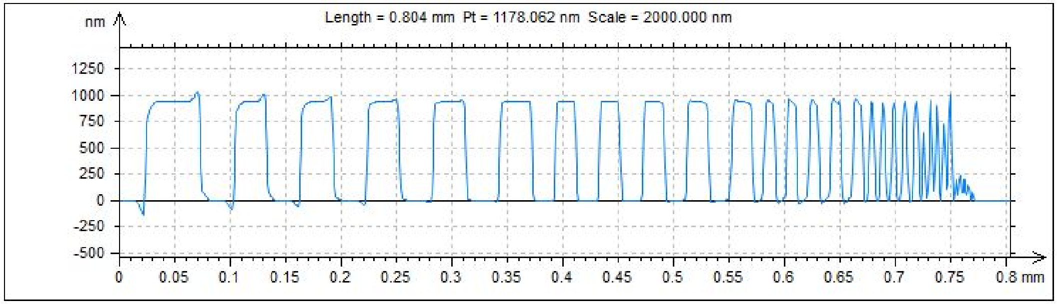


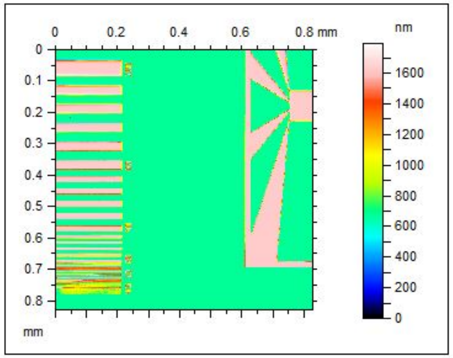
10X





20X

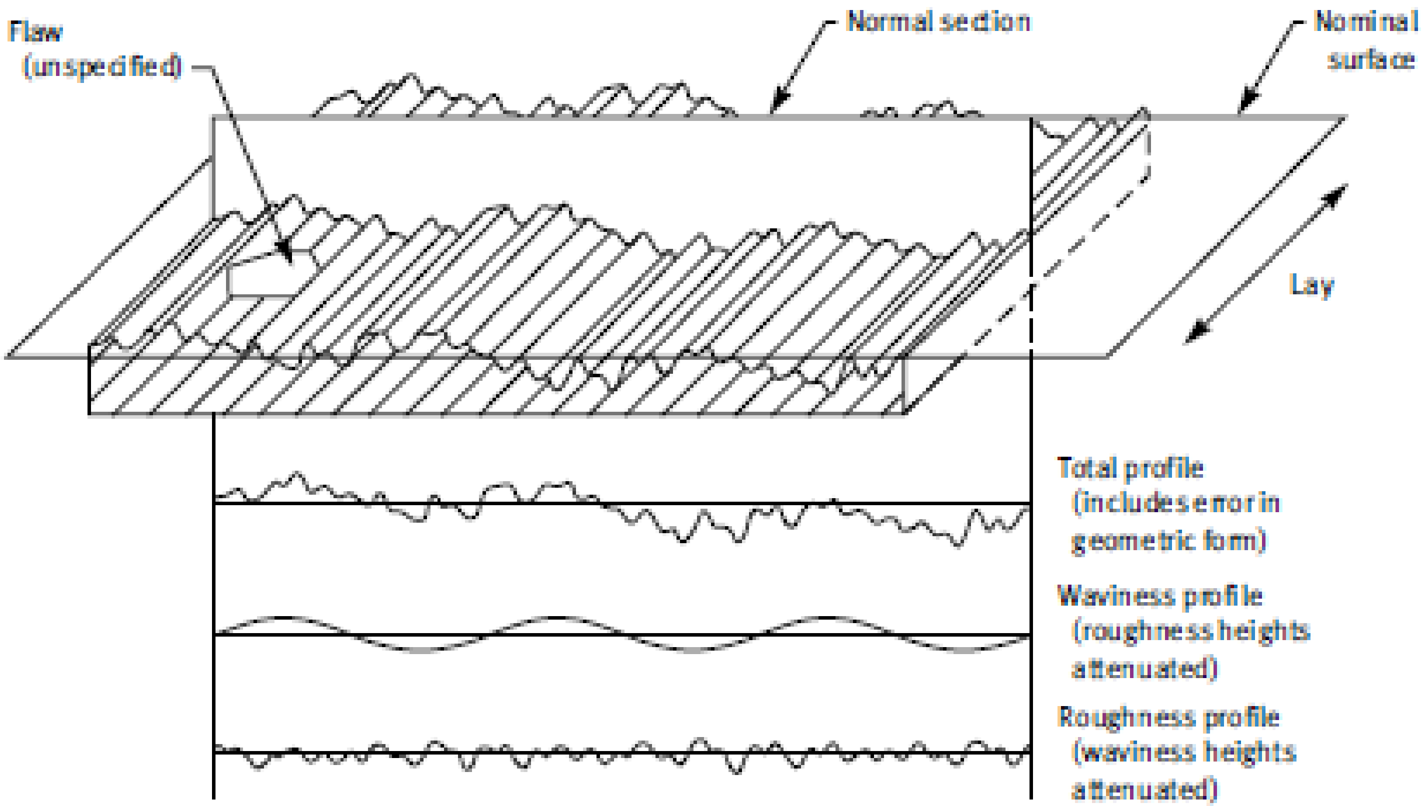




Contact instruments

- The earliest surface topography tools
- Stylus contacts surface, and traces a profile (or multiple profiles); typically spans the least expensive to very expensive
- Performance usually commensurate with price
  - More expensive usually have greater options w/ data & signal processing, greater sensitivity, span-of-motion, simultaneous measurement of form and finish
- Before we go into instruments—more depth on how topography is processed

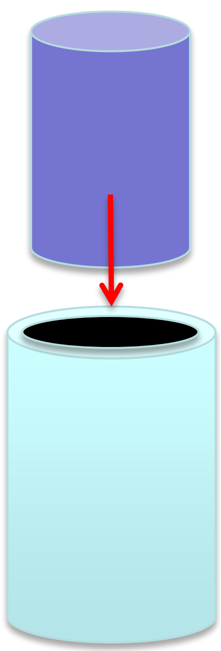
Remember: Parameters reduce millions of points to 1 parameter



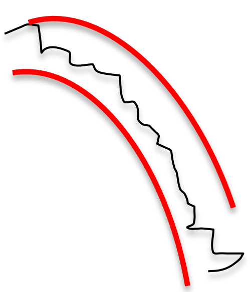
- Original instruments were stylus profilers that would collect a series of points from a line trace
- Electronic high-pass filter to retain only the high frequency (short wavelength) content: Roughness profile
- Average the output to get “average” roughness

Form & waviness

- Geometric specifications for parts ensure, among other things, assemblablity: Suppose design to assemble purple part into light blue part (e.g. piston/cylinder in engine)



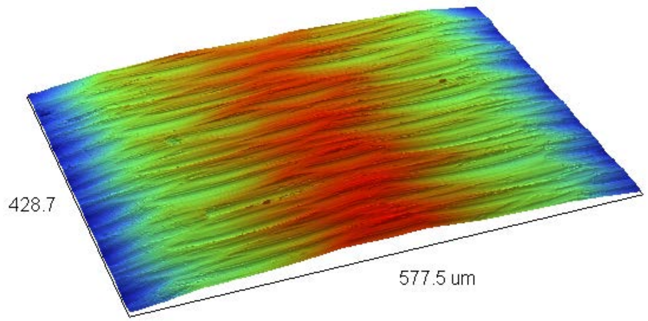
- Manufacturing imperfections, etc.—cannot (and should not) design plug same size as hole!
- “Form” specifications establish “acceptable boundaries”
- Traditional machining: Machine geometry & imperfections dominate allowable form & “waviness”; tool/cutter/material interactions dominate “roughness”



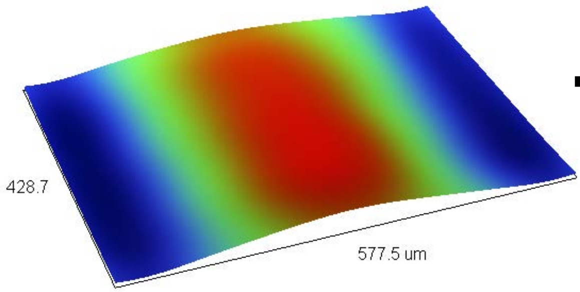
Filtering

- Selection of filters to separate roughness from form & waviness is critical
- Communication of filter settings is critical
- For the most part, “recommended” filter settings in standards

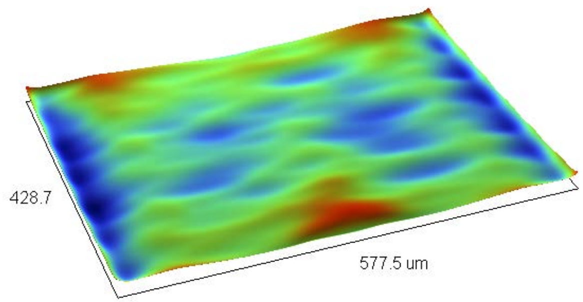
Measured surface



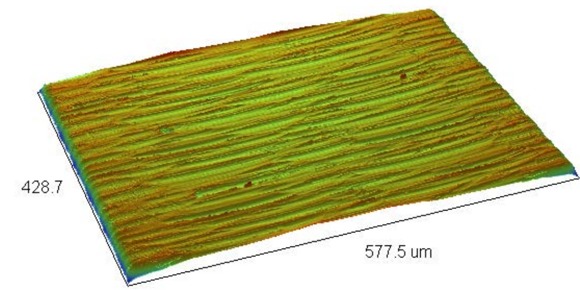
=



\+



\+



form + ***waviness*** + ***roughness***

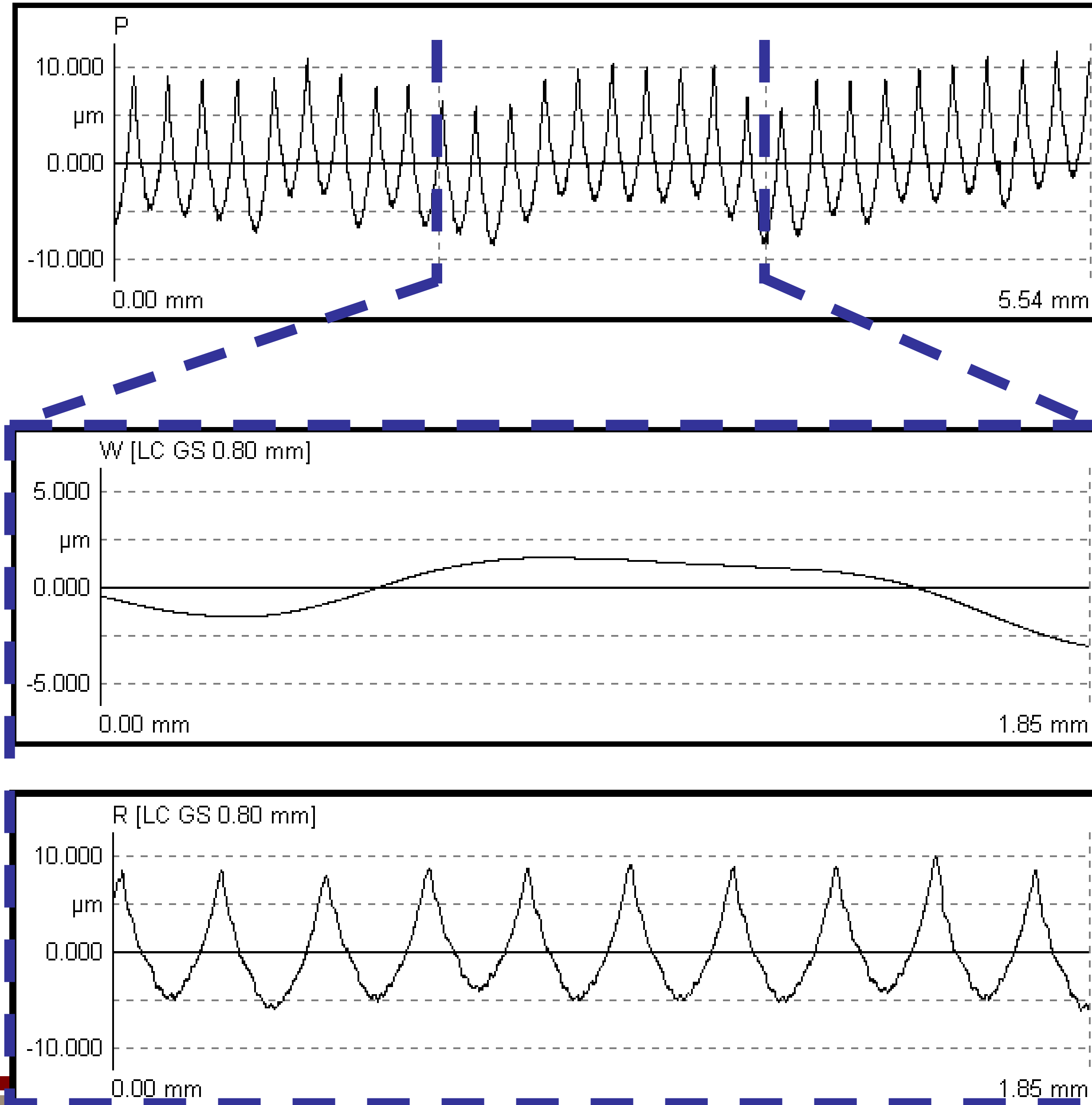
Filtering: waviness, roughness

Sandia National Laboratories

Trace – with leveled with the mean set to zero

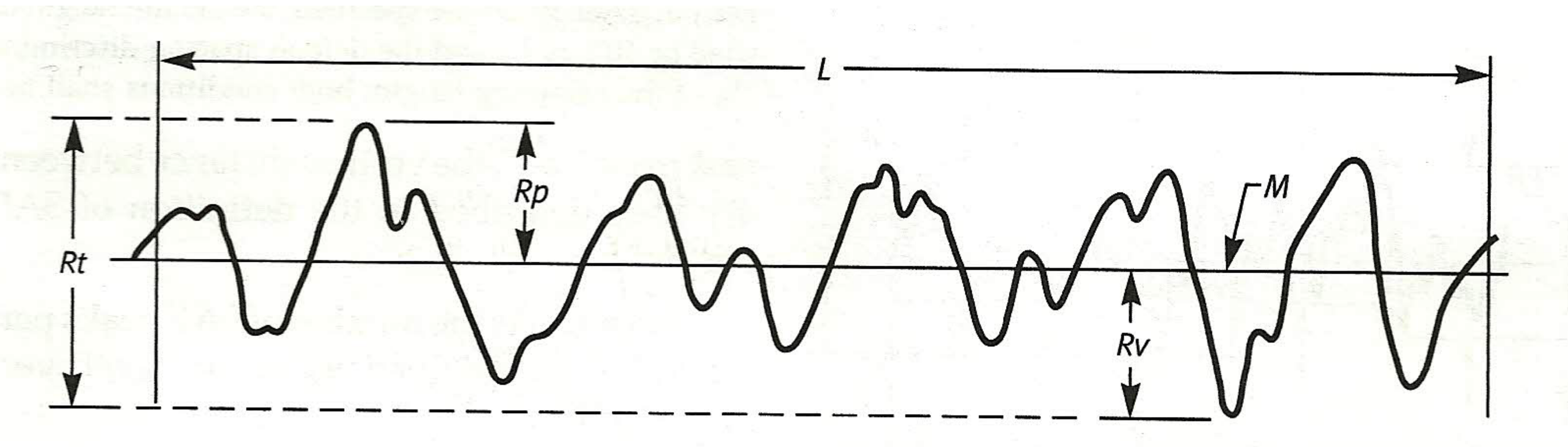
Waviness – "Roughness removed"

Roughness – "Waviness removed"



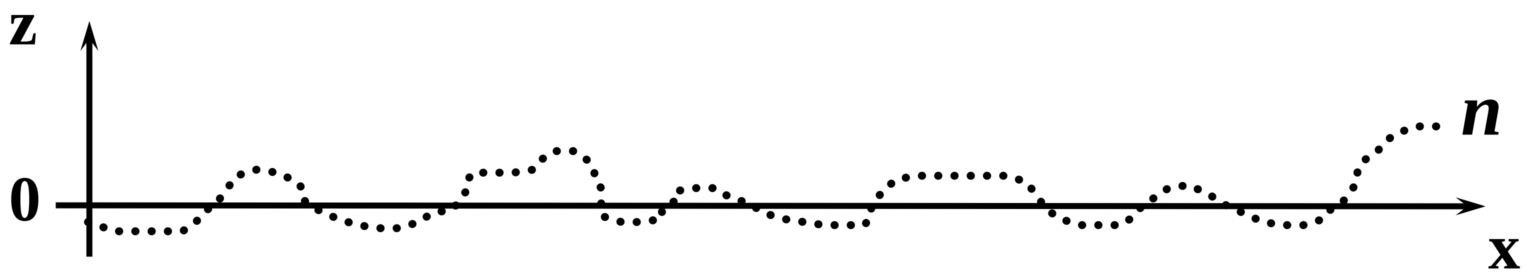
Some height parameters

- Ra = arithmetic average height (most used)
- Rt   maximum peak-to-valley
- Rp peak height
- Rv valley depth   Rt = Rp + Rv



Traditional Topographic Characterization

S: surface z=z(x,y) R: profile z=z(x)



arithmetic average:

$$\text{Sa or Ra} = \frac{1}{n}\sum_{n}^{1} |z|$$

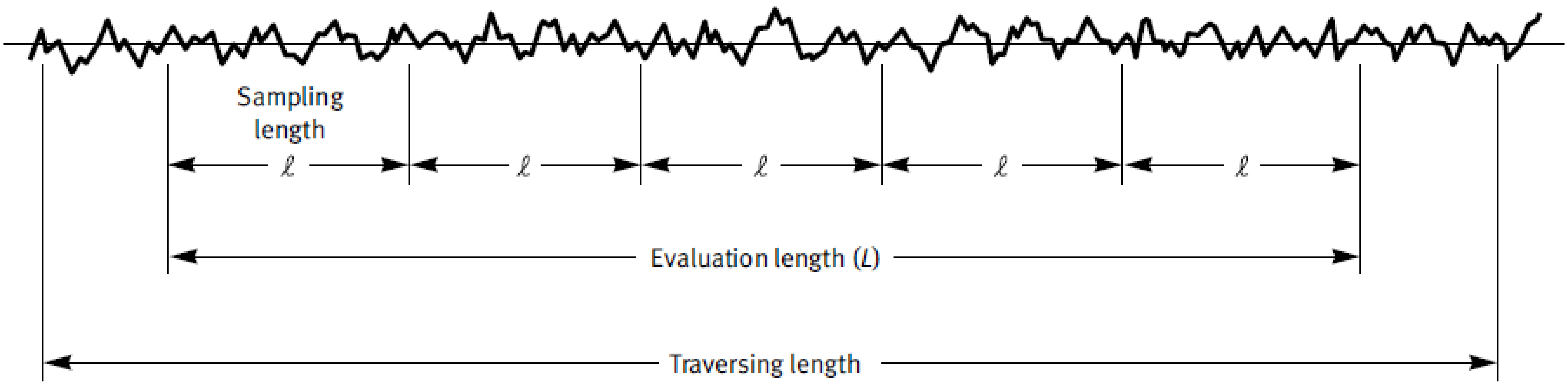
root mean square:

$$\text{Sq or Rq} = \sqrt{\frac{1}{n}\sum_{1}^{n} z^2}$$

Mechanical instruments

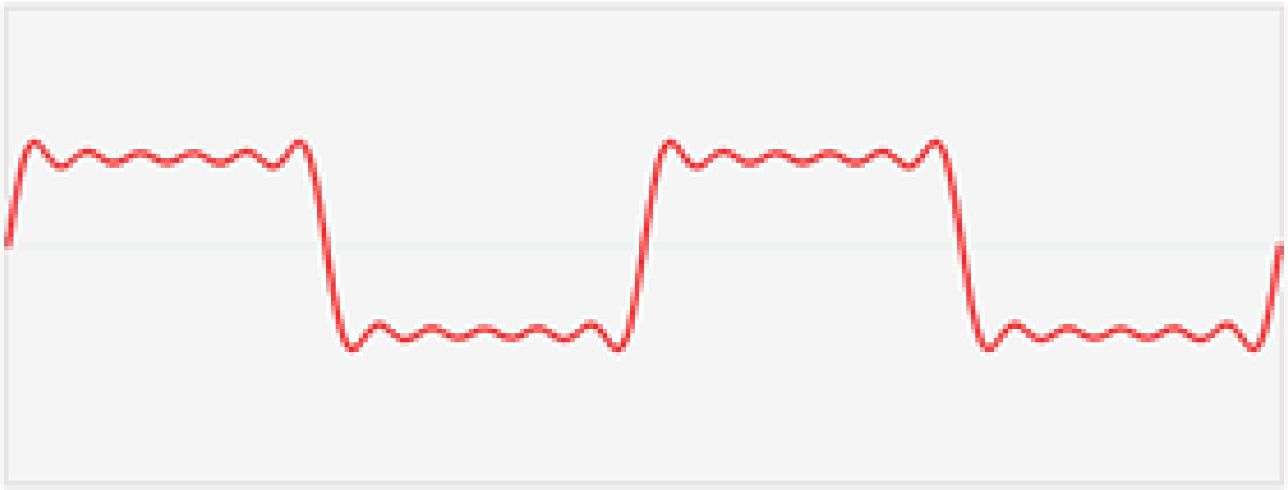
- Traverse length > evaluation length in order to account for “landing” and “take-off” transients
- Multiple sampling lengths in an evaluation length to help with filtering “before” digital computers
- Standards give guidance on what the sampling length ***should*** be, based on past research—sampling length is based on cutoff length, which is based on expected (& measured) roughness

Fig. 1-7 Surface Profile Measurement Lengths



-Any (continuous) line can be expressed as a sum of sines & cosines (or other orthogonal functions)

-A filter blocks certain frequencies; passes other frequencies



Let animation play to show square wave decomposition

Gaussian filter characteristics

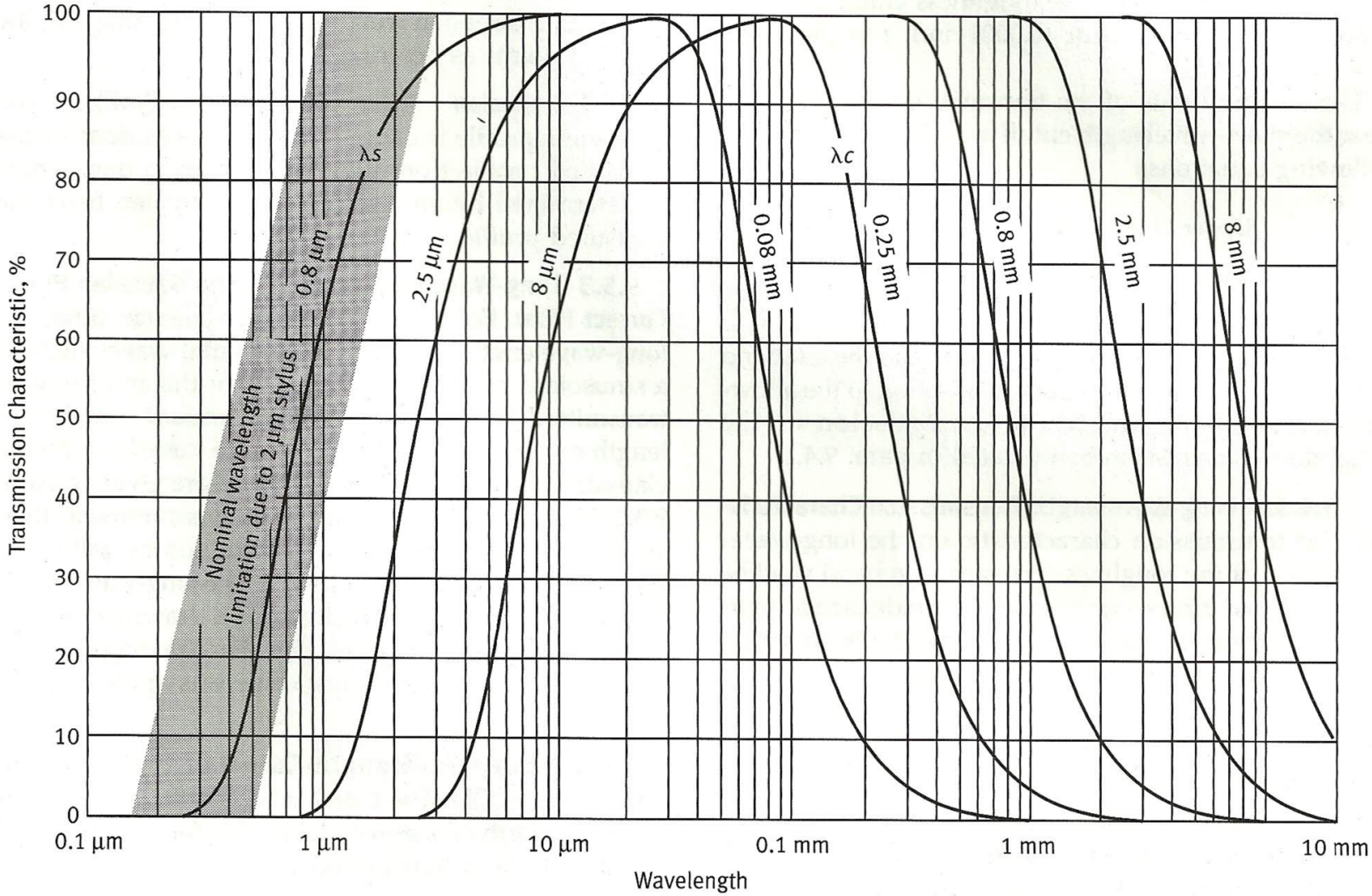
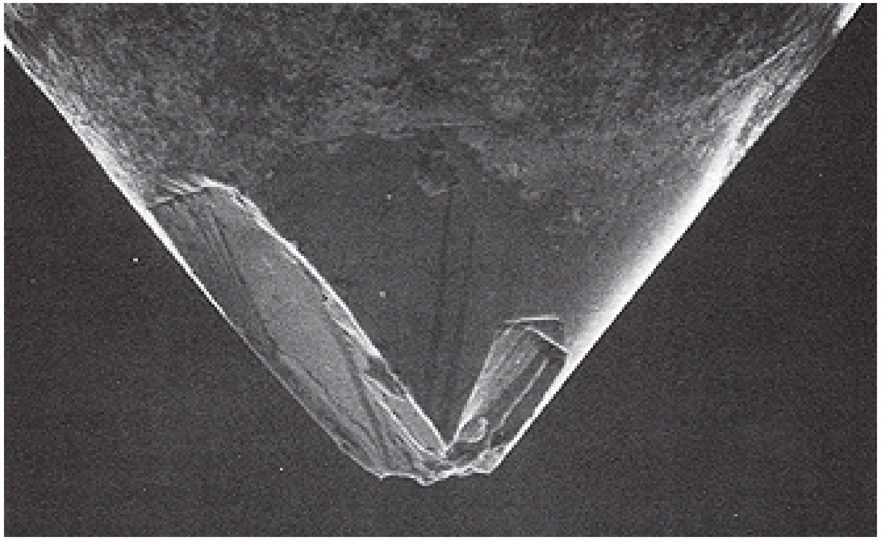
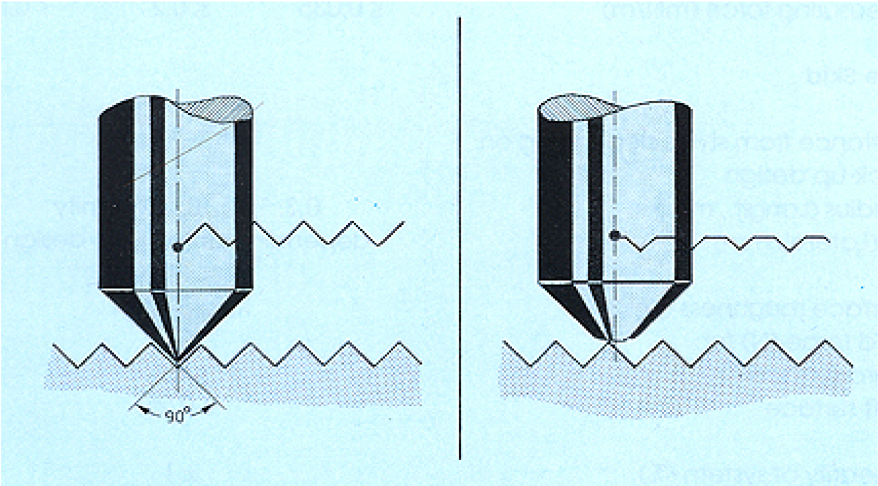


Fig. 9-2 Gaussian Transmission Characteristics Together With the Uncertain Nominal Transmission Characteristic of a 2 μm Stylus Radius

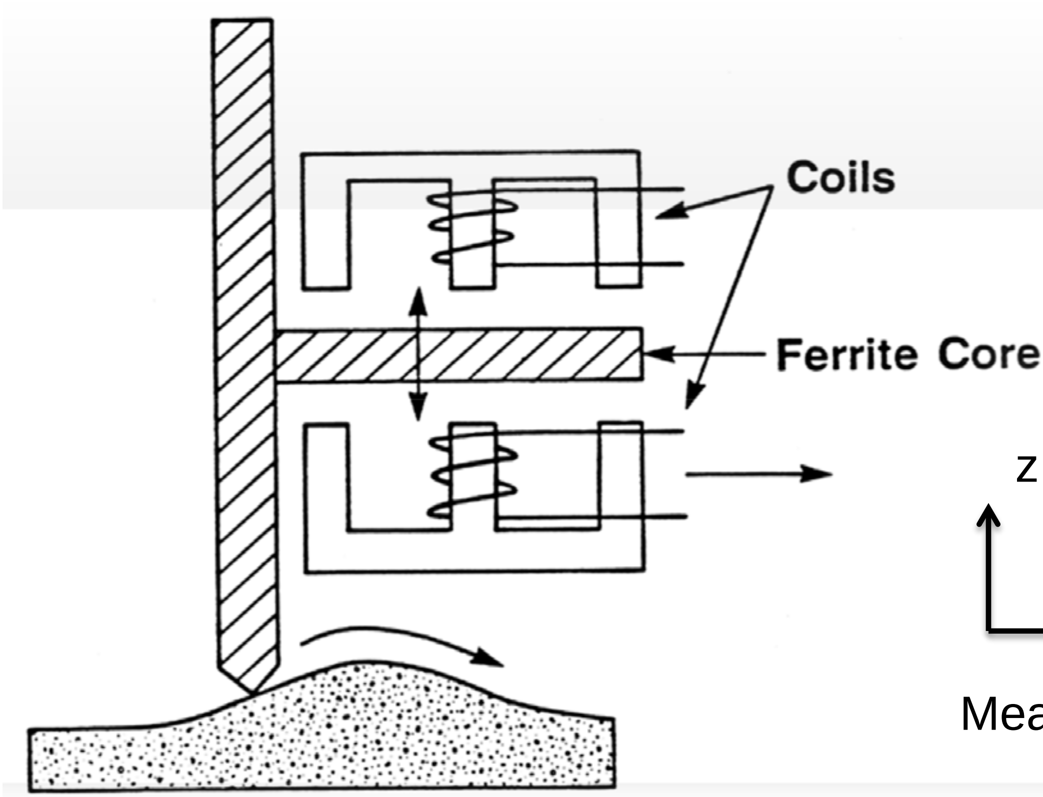
Stylus/surface interaction acts as a (nonlinear) low-pass filter

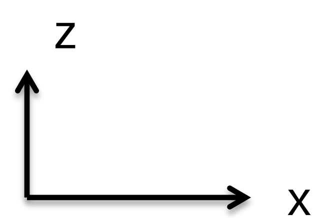
- Smaller stylus radius can "read" higher spatial frequency (shorter spatial wavelength)
- The condition of the stylus can affect your reading. An increase in the stylus radius, due to damage, will prevent the tip from entering the valleys giving substantially lower roughness values.





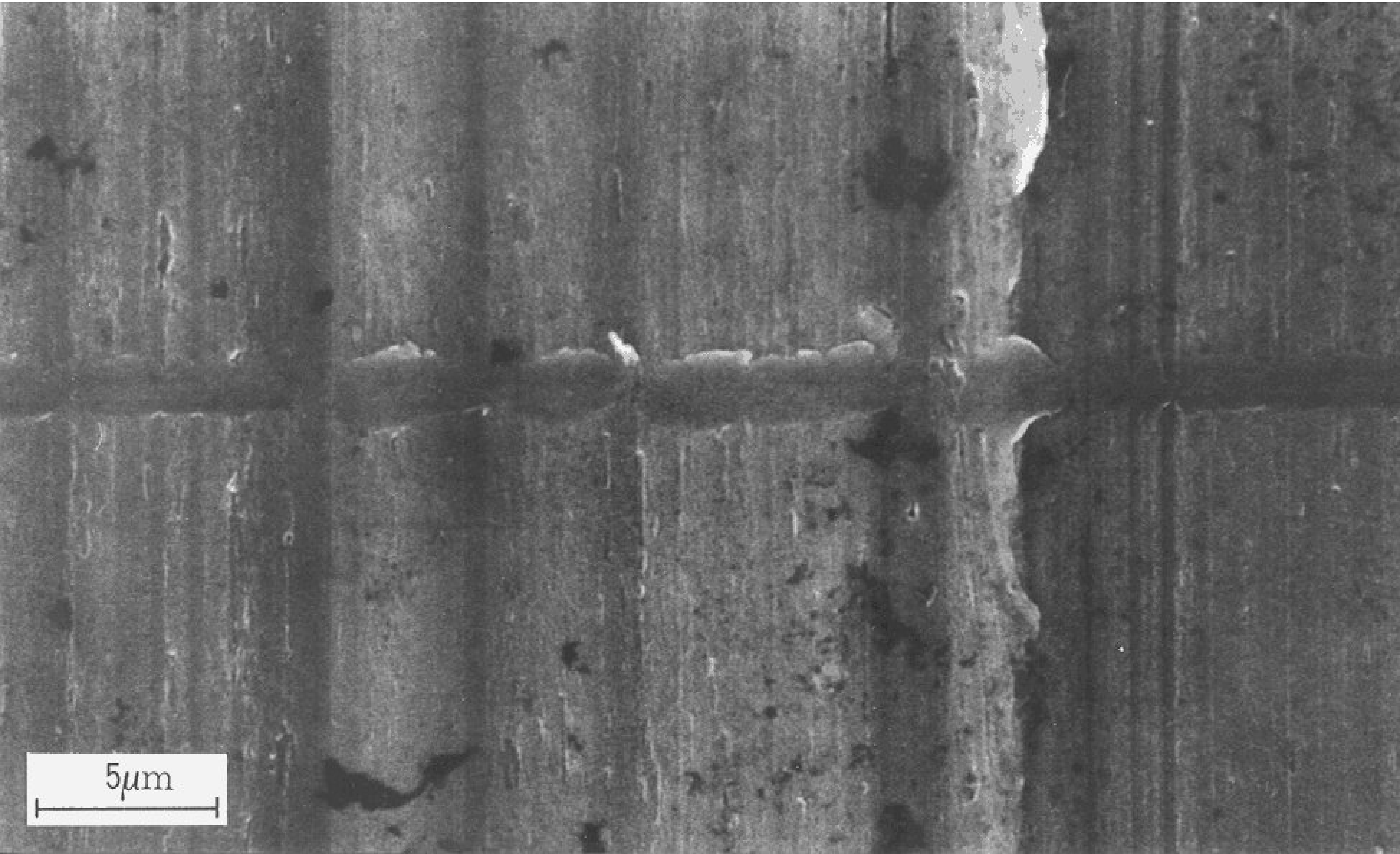
Typical stylus instrument schematic





Measure z as f(x)

Stylus can affect surface – SEM micrograph of a stylus trace on a turned aircraft aluminum alloy

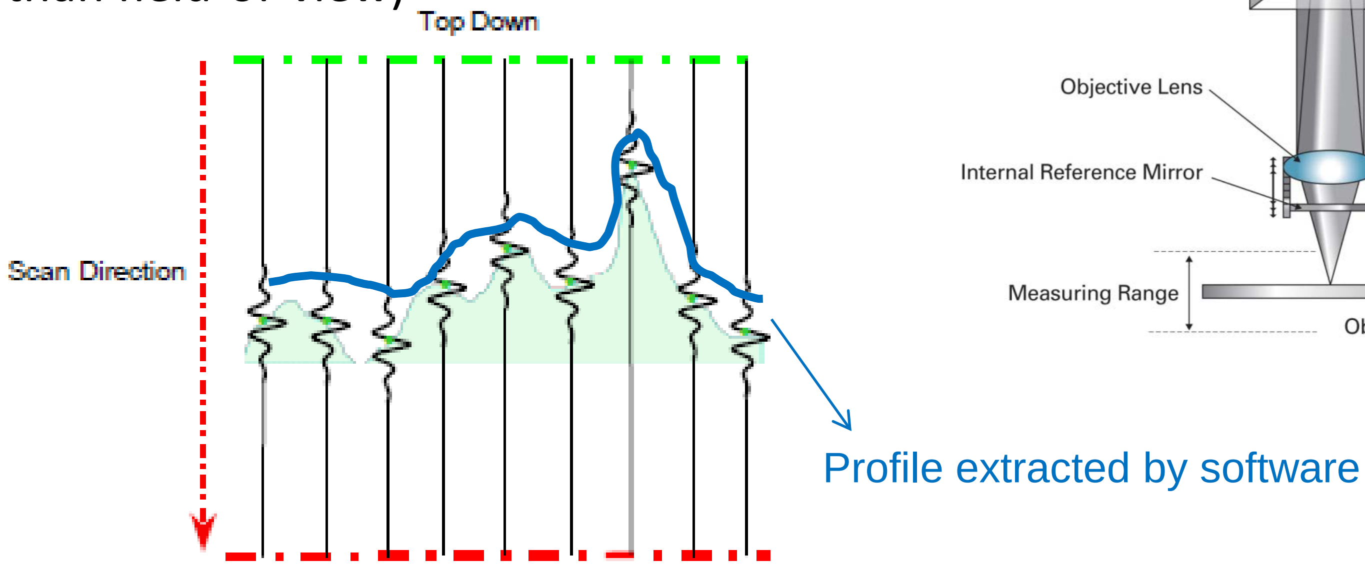


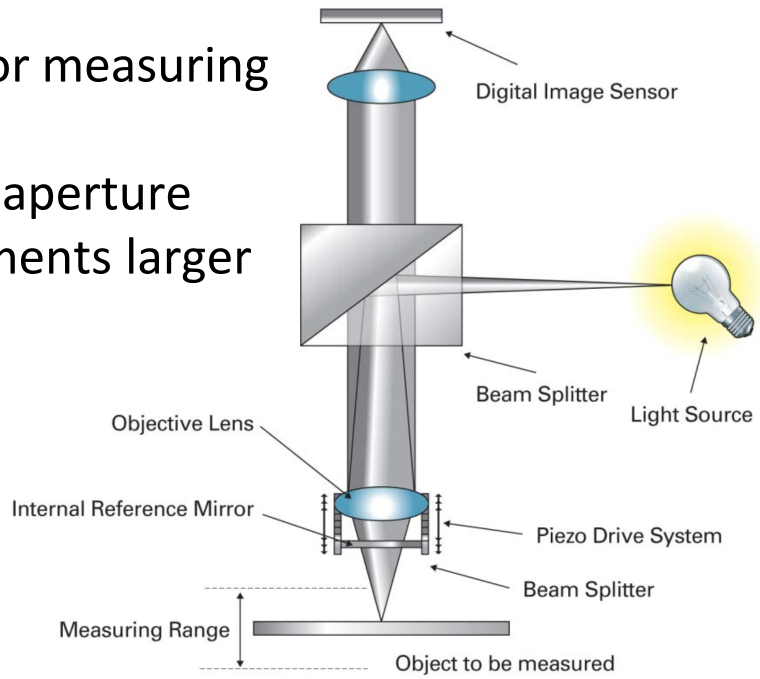
Non-contact methods

- Typically captures z-points over a “large” x-y area
  - Note that it is also possible to capture area measurements with stylus contact methods by stitching y motion & x/z scans
  - Note that some non-contact methods capture “point-at-a-time”
- Typically optical
  - White light interferometers (scanning white light interferometers etc.)
  - Confocal scanning
  - Focus variation methods
  - Structured light methods

Coherence Scanning Operating Principles

- Measures vertical (z) features
- x,y (lateral) are like conventional microscope (image/pixel)
- Resolves vertical to 0.1 nm (or better)
- Software (both embedded and workflow) for measuring and analyzing surface geometry map
- Slope limitation due to objective numerical aperture
- Computer control for "stitching" (measurements larger than field-of-view)





Confocal

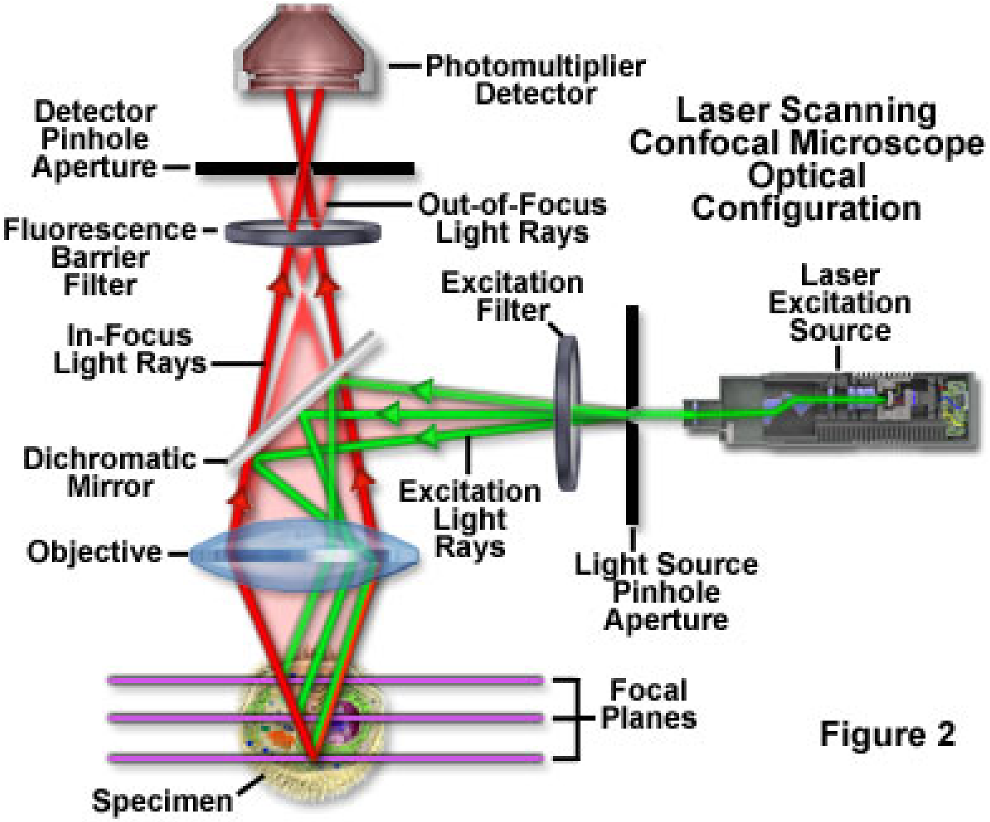
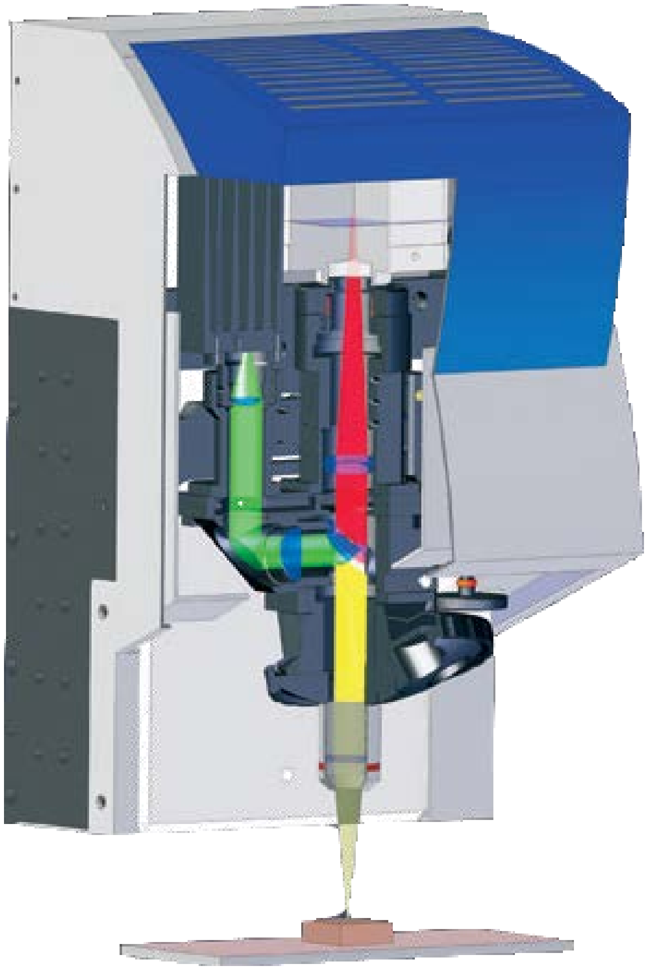
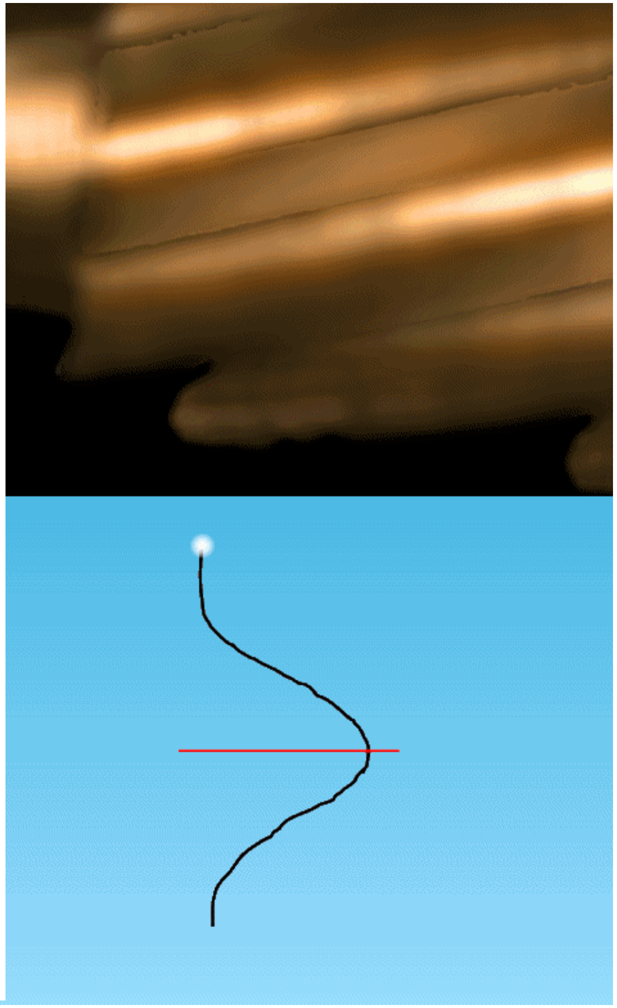


Figure from Olympus

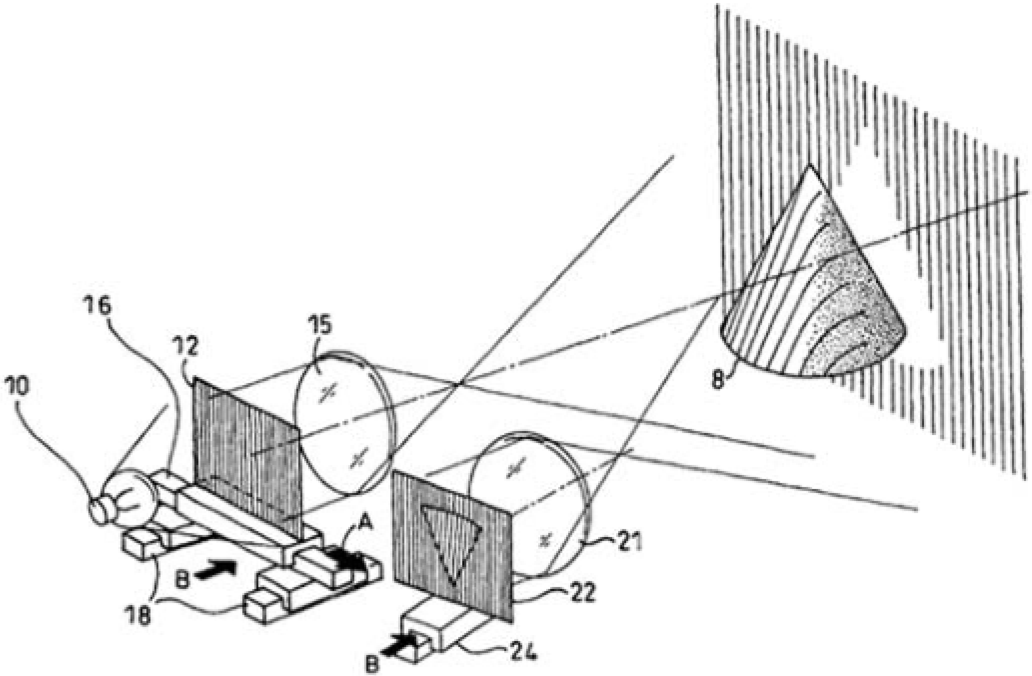
Focus variation





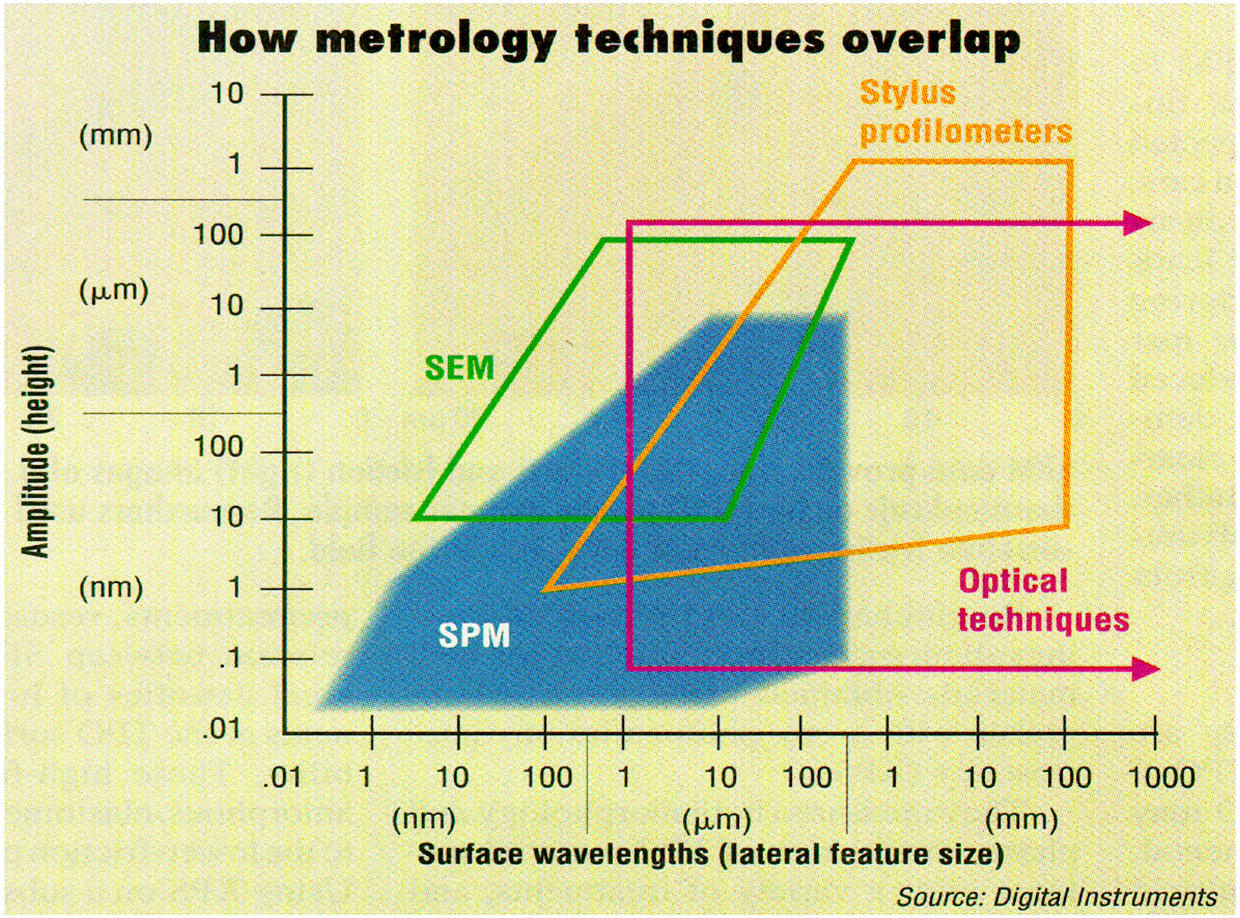
Structured light methods

- Such as Moire Fringe Projection methods



Different tools have different “sweet spots”

Use Stedman diagram to identify appropriate tools for your surface topography needs:
Stedman, M. “Basis for comparing the performance of surface-measuring machines”, *Prec. Eng. V9(3)*, p. 149-152, July 1987



Parameters

- Reminder: When looking at surface texture/surface topography, a “parameter” is a single number that represents the surface
- The parameter (hopefully) has correlation with performance characteristics
- Parameters are put on drawings, and are typically a manufacturing contractual requirement—for example contractual requirements on size, distance, etc.—also requirements on texture, such as Roughness average R_a

- P→Primary profile (line); R→Roughness (of a line); W→Waviness (of a line); S→Areal (equivalent to R, but of a surface); Pt=“Profile max peak minus min valley (total)”; Rt=Roughness max peak minus min valley, etc.

Typical parameters

- Height (amplitude) parameters
- Spacing parameters
- Shape parameters, hybrid parameters
- Statistical parameters
- Parameters are described in both ASME and ISO documents
  - We will revisit in greater detail later

- If you ***specify*** a parameter, you should make sure that the parameter you specify has an impact on the desired performance!

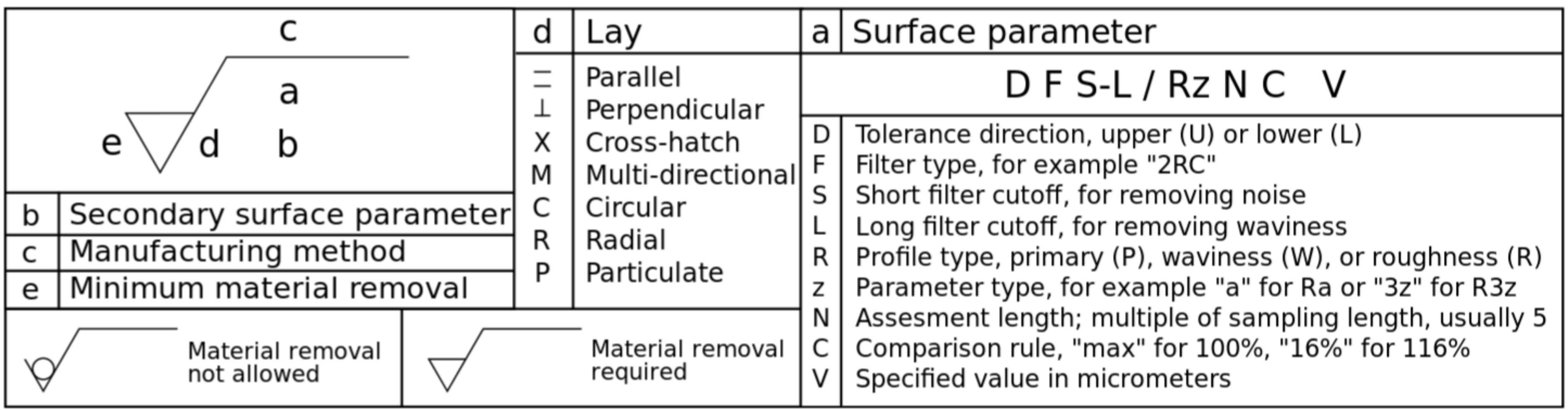
Surface topography standards (as of 2012)

Sandia National Laboratories

Standard number	Short title (GPS→Geometrical Product Specifications)
ASME Y14.36M:1996	Surface texture symbols
ASME Y14.5:2009	Dimensioning and Tolerancing
ASME B46.1:2009	Surface Texture (Surface Roughness, Waviness, and Lay)
ISO 1302:2002	GPS-Surface texture-Indication of texture in product documentation
ISO 4287:1997	GPS-Surface texture-Profile method-terms, definitions…
ISO 4288:1996	GPS-Surface texture-Profile method-Rules and procedures
ISO 5436-1:2000	GPS-Surface texture-Profile method-measurement stds
ISO 5436-2:2000	GPS-Surface texture-Profile method-software
ISO 8785:1998	GPS-Surface imperfections-terms, definitions …
ISO 12085:1996	GPS-Surface texture-Profile method-Motif parameters
ISO 12179:2000	GPS-Surface texture-Profile method-Calibration of stylus instruments
ISO 13565-1:1996	GPS-Surface texture-Profile method-stratified functional-filtering
ISO 13565-2:1996	GPS-Surface texture-Profile method-stratified functional-height ratio
ISO 13565-3:1996	GPS-Surface texture-Profile method-stratified functional-material prob
ISO 16610-1:2006	GPS-Filtration-overview
ISO 16610-20:2006	GPS-Filtration-linear filters-basic concepts
ISO 16610-21:2011	GPS-Filtration-linear filters-Gaussian filters
ISO 16610-22:2006	GPS-Filtration-linear filters-Spline filters
ISO 16610-28:2010	GPS-Filtration-linear filters-end effects
ISO 16610-30:2009	GPS-Filtration-Robust profile-basic concepts
ISO 16610-31:2010	GPS-Filtration-Robust profile-Gaussian regression
ISO 16610-32:2009	GPS-Filtration-Robust profile-Spline
ISO 16610-40:2006	GPS-Filtration-Morphological-basic concepts
ISO 16610-41:2006	GPS-Filtration-Morphological-Disk and horizontal line segment filters
ISO 16610-49:2006	GPS-Filtration-Morphological-Scale space techniques
ISO 25178-2:2012	GPS-Surface texture-Areal-Terms, definitions
ISO 25178-6:2010	GPS-Surface texture-Areal-Classification of methods
ISO 25178-601:2010	GPS-Surface texture-Areal-characterisitics of stylus instruments
ISO 25178-602:2010	GPS-Surface texture-Areal-characteristics of confocal chromatic probe
ISO 25178-701:2010	GPS-Surface texture-Areal-Calibration and standards for stylus instr.

Symbols on drawings

- Symbols generally ASME Y14.36M:1996; ISO 1302:2002
- Generally graphical shorthand—eg rather than “surface bounded by two parallel planes separated by 0.10 mm,” ⏥ 0.10
- If you design—fully specify the parameter, e.g.
  - Parameter (Ra? Rq?) & acceptable limits?
  - Mean line? (Least square mean line)
  - Eval length?
  - Short wavelength & long wavelength filters (both length and filter type; usually Gaussian filter)

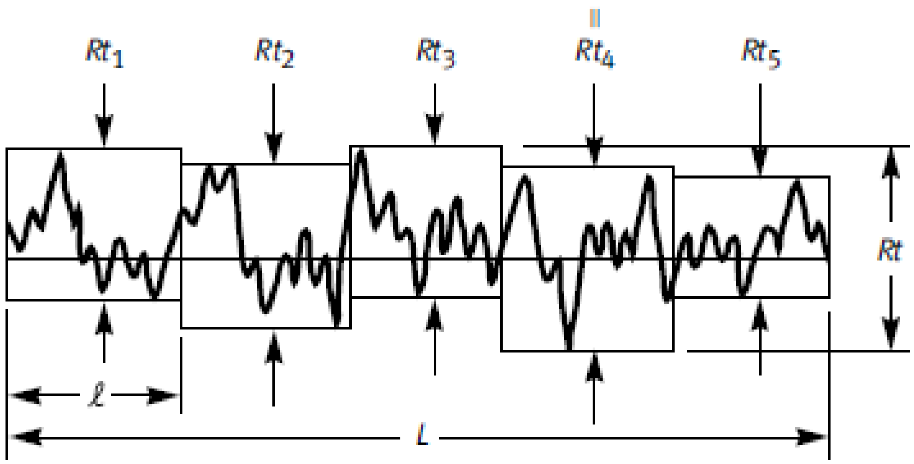


Instruments, parameters

- Typical workflow:
  - Instrument collects points
  - Points are filtered because of basic physics (optical limits, contact limits, etc.) (user has little control)
  - Points are filtered because of instrument limits (frequency response of stylus?) (user has little control)
  - Instrument software or firmware processes data:
    - Sampling length, evaluation length, cutoff filters (user has controls, but the controls are sometimes hidden)
    - Calculation of parameter (user clicks the checkbox on the screen or pushes a button)
  - Report is produced (least expensive instruments: A single number on the display. Most expensive instruments: Color screen shots etc.)

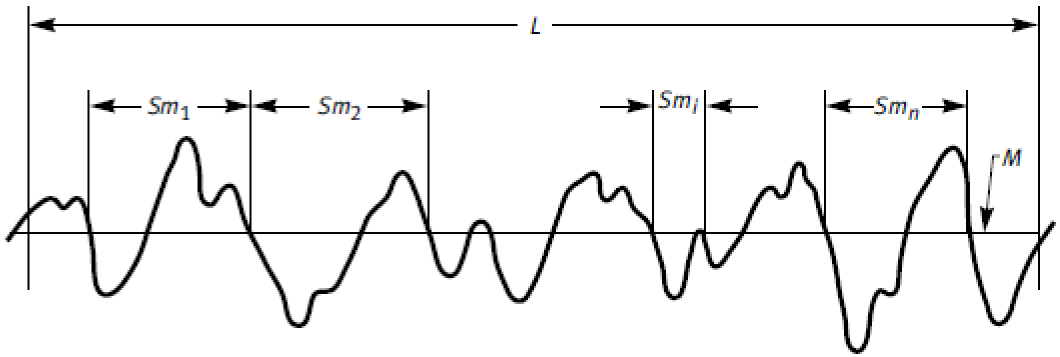
Height parameters

- Ra (also Sa, etc.)→ average of deviations from mean line
- Rq →rms of deviations from mean line
- Rt→max peak minus min valley over a sampling length
- Rz→average of *n* Rt's (typically 5 Rt's, where each sampling length = 1 cutoff length)



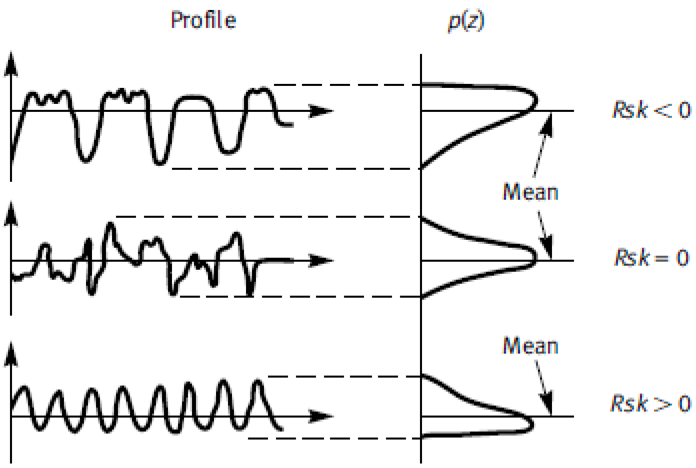
Spacing parameter

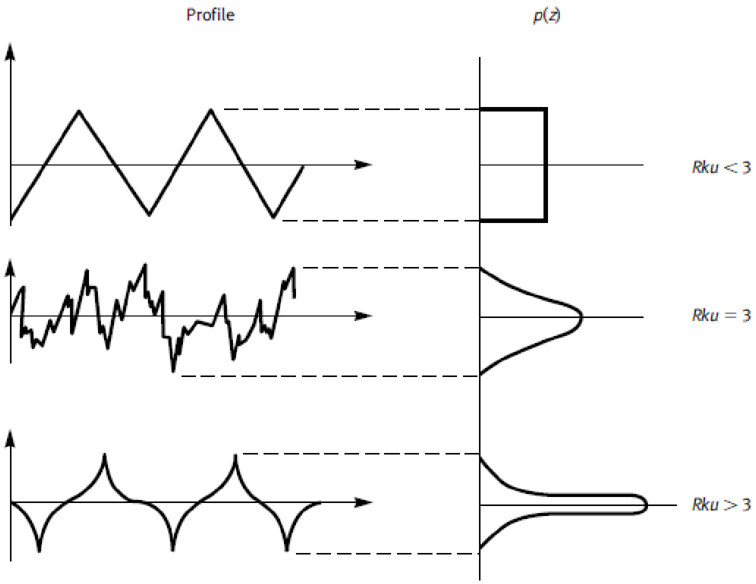
- Rsm→Mean spacing of profile irregularities: Average of the Sm's below



Shape parameters (statistical)

- Rsk (skewness, >0→more hills; <0→more valleys)
- Rku (kurtosis, pointiness of profile; =3→roughly gaussian; >3→pointy; <3→not as pointy)



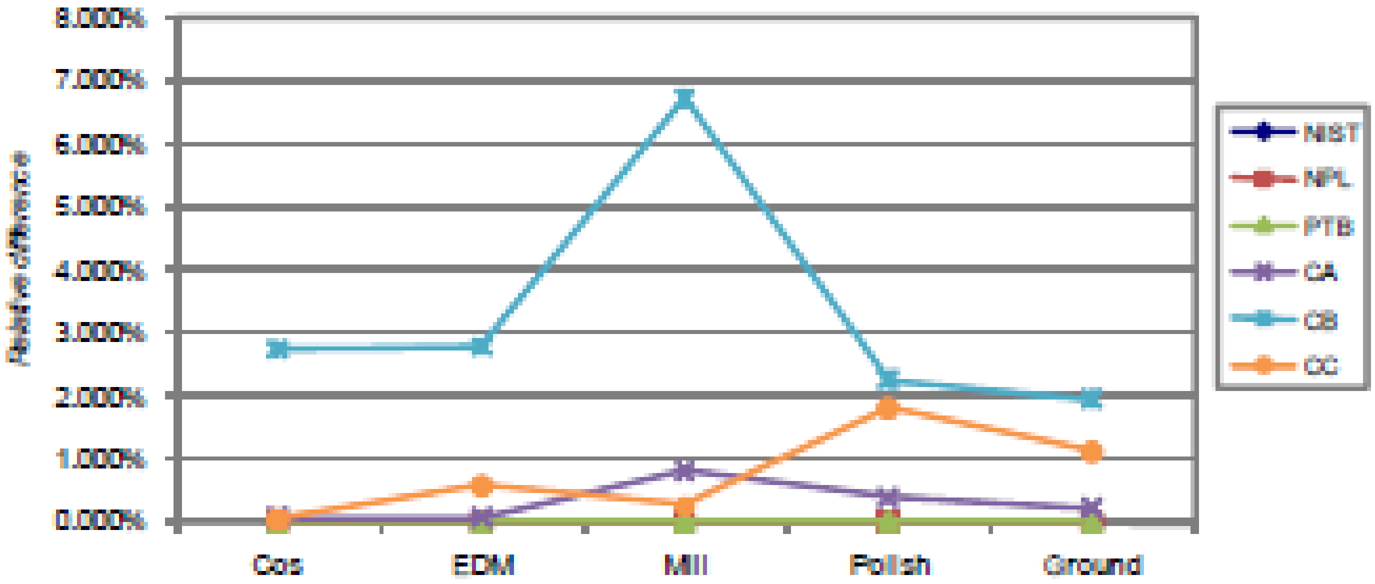


Software validation

- If you have a moderately complex instrument, there is software
- Does it perform calculations correctly?

- 5 different profiles
- 3 NMI softwares
- 3 commercial softwares
- Ra calculation

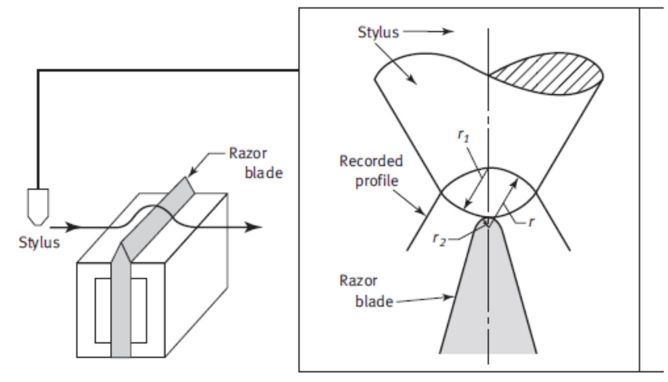
Displaying relative difference of results, normalized to mean

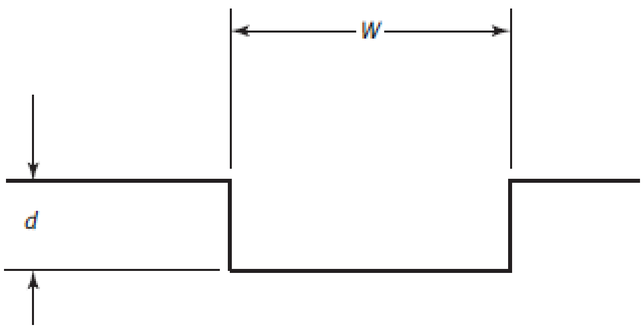


From NPL Report

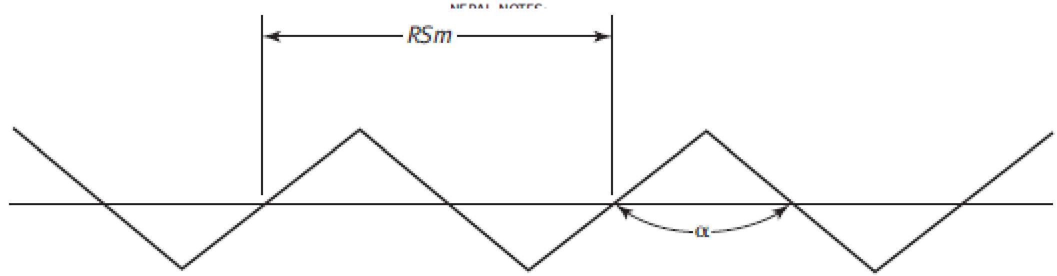
Good practices

- Precision reference specimens:
  - Amplification (step height); “Type A” specimen
  - Stylus condition; “Type B” specimen—best test is razor blade test (if you can do it)
  - Parameter specimen, good for checking; “Type C”
  - Performance specimen w/ irregular profile; “Type D”





Type A single groove



Type B or C

Good resources

- ASME B46.1:2009
- NPL Good Practice Guides (free w/ e-mail registration)
- Taylor-Hobson booklets (free w/ e-mail registration)