Requirement of high surface finish

- Lenses, mirrors, ICs, etc. (Optics & electronics)
- Medical: Implant, surgical instruments, etc.
- Many others
- Material properties: High fatigue life, toughness, wear resistance, etc.
- Products: Die/molds, RP, Turbine blades, bearings, etc.
- Integration: Assembly, multilayers, coatings, etc.
- Microfluidics: Channels, nozzles, mixtures, etc. (flow, pressure drop, etc.)

Images:
- www.Interspectrum.ee
- Fraunhofer, Germany
- www.extrudehone.com
Surface and texture

- Surface → The boundary that separates an object from another object, substance, or space…”
- Texture → The composite of certain deviations that are typical of the real surface. It includes roughness and waviness…”

Surface Texture: Why Is It Important?

Texture is a 'fingerprint' of the whole of the manufacturing process

→ Very sensitive end product of a long sequence of operations ↔
→ Any deviation in the manufacture reflects itself in the texture ↔

If you make sure that the surface texture is within certain bounds ensures similar manufacture → it ensures similar performance of the workpiece.

- Rolling
- Sliding
- Sealing
- Load Bearing
- Cosmetic
- Lubricant Retention
- Friction
- Wear
- Adhesion

Components of surface texture

**Roughness**
Comprising of irregularities that occur due to the mechanism of the material removal process: tool geometry, wheel grit, or the EDM spark

**Waviness**
Component of the surface texture upon which roughness is superimposed, resulting from factors such as machine or part deflections, vibrations and chatter, material strain, etc.

**Profile**
The overall shape of the surface - ignoring roughness and waviness variations - is caused by errors in machine tool slideways

Graham Smith, Industrial Metrology, Springer
Cost comparison of surface finishing

- What Texture do you need?
- How much does it cost?
- If a smooth surface is the requirement then this takes a significantly longer time to produce than an apparently rougher surface.
- High surface finish $\rightarrow$ high resolution metrology $\rightarrow$ high cost of measuring instrument.
- $3\ \mu m \rightarrow 0.5\ \mu m$
- $0.5\ \mu m \rightarrow 100\ nm$
- $100\ nm \rightarrow 50\ nm$
- $50\ nm \rightarrow 10\ nm$
- $10\ nm \rightarrow <1\ nm$

Smother is better ???

Graham Smith, Industrial Metrology, Springer
Importance of surface irregularities

- The shape and size of irregularities on a machined surface have a major impact on the quality and performance of that surface.
- The quantification and management of fine surface irregularities is necessary to maintain high product performance.

Quantification of surface irregularities

- Differences in these irregularities impact the quality and function of the surface.
- Irregularities affect the performance of the end product in aspects such as friction, durability, operating noise, energy consumption and airtightness.

Graham Smith, Industrial Metrology, Springer
Early age of surface roughness measurement

- Early efforts to define surface finish utilized identified reference surfaces with different visual appearances that could be compared for qualitative surface characterization.
- Machinists would literally scratch the surface of their parts with their thumbnail and compare them with the reference.
- General Electric was an early U.S. developer and supplier of standardized visual standards.
  - Similar standards produced by Flex-Bar and other manufacturers are still available for purchase and use.
- It was a simple go/ no-go procedure.
- Not data was gathered and no mathematical analysis conducted.
- They were subjective (no means of quantifying a surface)
Instruments for Texture Measurement

- Comparison of the capabilities of instrumentation can be achieved by using plots in the amplitude–wavelength plane.

2D Measuring methodology

- Linear roughness measurement (profile method type)
- Use of a single line on the sample surface
- Roughness in the surface is measured along an arbitrary straight line
- A contact stylus is commonly used to perform linear measurement

http://www.photonics.com/Article.aspx?AID=58301 / NISTIR 89-4088 (Surface finish metrology tutorial)
Limitation of stylus based instruments

Stylus finite size affects the accuracy

The curve tends to round the peaks (I) and reduce the depth of the valleys (II), although the peak height is not affected (III)

Whenever a stylus encounters a re-entrant feature the stylus tip loses partial contact with the profile and as a result will remove this feature from the trace.

Graham Smith, Industrial Metrology, Springer
Limitation of stylus based instruments

Hard needle-shaped stylus is more likely to scratch the surface of a soft specimen.

With adhesive specimens, on the other hand, the stylus can attach to the specimen and be damaged when pulled.

The side of the stylus (non-measuring surface) is in contact with the component. → Stylus flanking → No useful information about the surface.

Limitation of stylus based instruments

Contact surface roughness gages cannot measure micro surface contours less than the stylus tip diameter.

Effect of traverse speed

- Signal frequency depends on the traverse speed.
- Measuring fine surface finish → typically a sharp stylus and slow traverse speed are used.
- Slow traverse speed ensures that the stylus tracks the surface and that the resulting frequencies do not exceed the mechanical and electronic bandwidth of the data acquisition system.

Graham Smith, Industrial Metrology, Springer
Separate the waviness and roughness

- Procedures needed to calculate surface roughness
  - Remove the underlying geometry shape
  - Separate out the waviness and roughness
  - Calculate surface roughness
- Filtering surface profiles involves running a "smoothing" filter through the primary data.
- Shorter wavelengths fall into the roughness profile.
- Longer wavelengths appear in the waviness profile.


Sampling and evaluation length

- **Sampling length**: The length in the direction of the x-axis used for identifying the irregularities that characterize the profile under evaluation.
- It implies that structure in the profile occurring over longer lengths will not be applicable in this particular evaluation.
- **Evaluation length**: the total length in the x-axis used for the assessment of the profile under evaluation.
Effect of cutoff length

- It is used to confine to roughness measurement in the presence of waviness.
- Low cut off value → shorter wavelength on the surface gets captured.
- Machining marks are widely spaced → long cutoff to measure.
- Finishing / polishing marks are closely spaced → shorter cutoff to measure.
- The value of the sampling length is a compromise.
  - It should be long enough to get a statistically good representation of the surface roughness.
  - If it is made too big, longer components of the geometry, such as waviness, will be drawn in if present and included as roughness.

### Recommended Cut-off (ISO 4288-1996)

<table>
<thead>
<tr>
<th>Periodic Profiles</th>
<th>Non-Periodic Profiles</th>
<th>Cut-off</th>
<th>Sampling Length/Evaluation Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacing Distance</td>
<td>Rz (µm)</td>
<td>Ra (µm)</td>
<td>λc (mm)</td>
</tr>
<tr>
<td>RSm (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;0.013-0.04</td>
<td>To 0.1</td>
<td>To 0.02</td>
<td>0.08</td>
</tr>
<tr>
<td>&gt;0.04-0.13</td>
<td>&gt;0.1-0.5</td>
<td>&gt;0.02-0.1</td>
<td>0.25</td>
</tr>
<tr>
<td>&gt;0.13-0.4</td>
<td>&gt;0.5-10</td>
<td>&gt;0.1-2</td>
<td>0.9</td>
</tr>
<tr>
<td>&gt;0.4-1.3</td>
<td>&gt;10-50</td>
<td>&gt;2-10</td>
<td>2.5</td>
</tr>
<tr>
<td>&gt;1.2-4.0</td>
<td>&gt;30</td>
<td>&gt;10</td>
<td>8</td>
</tr>
</tbody>
</table>

Measured profile without electrical filtering

With 0.8 mm cutoff, Ra = 4 µm

With 0.25 mm cutoff, Ra = 2 µm

With 0.8 mm cutoff, Ra = 1

Surface Texture, Surface Roughness, Waviness and Lay - ASME B46.1-2002
Ra (average roughness) – 2D parameter

- Why Ra? → ”Standard” → Limits of technology..circa 1930...
- Why Not Ra?
  - No spatial structure information
  - No difference between peaks/valleys

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

Same Ra value but different profile??

In some applications they will perform very differently as well.

Similar profile shape but different spacing between features

Sharp peaks
Deep valleys
Neither

Donald K. Cohen, Michigan Metrology, LLC
Visual distortion

- The peak-to-valley height of surface roughness is usually found to be small compared with the spacing of the crests.
- The relative proportions of height and length lead to the use of compressed profile graphs, the nature of which must be understood from the outset.
- It is essential, to note both magnifications → Fragile peaks and narrow valleys may represent quite gentle undulations on the actual surface.

- To cover a sufficient length of surface profile without unduly increasing the length of the chart, it is customary to use a much lower horizontal than vertical magnification.

David J. Whitehouse, Handbook of Surface and Nanometrology 2nd Ed. (2010)
Surface texture graphical symbol

- Roughness value Ra in micrometer or grade number
- Production method, treatment or coating
  - $c = $ Sampling length
  - $f = $ Other roughness value than Ra
- Machining allowance
- Direction of lay

- Surface texture obtained by any manufacturing process
- Surface texture obtained by material removal by machining operation
- Surface texture obtained by WITHOUT removal of material

Jigar Talati, Hexagon Design Centre / Graham Smith, Industrial Metrology, Springer
Method of indicating surface roughness

- The latest Indian Standard for method of indicating surface texture on technical drawings suggests the practice of giving the surface roughness value directly in micron as Ra value or by grade numbers.
- The earlier method of indicating surface roughness through triangle symbols is now rarely used.

<table>
<thead>
<tr>
<th>Roughness value (µm)</th>
<th>Roughness grade number</th>
<th>Roughness symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>N12</td>
<td>![Symbol for Ra 50]</td>
</tr>
<tr>
<td>25</td>
<td>N11</td>
<td>![Symbol for Ra 25]</td>
</tr>
<tr>
<td>12.5</td>
<td>N10</td>
<td>![Symbol for Ra 12.5]</td>
</tr>
<tr>
<td>6.3</td>
<td>N9</td>
<td>![Symbol for Ra 6.3]</td>
</tr>
<tr>
<td>3.2</td>
<td>N8</td>
<td>![Symbol for Ra 3.2]</td>
</tr>
<tr>
<td>1.6</td>
<td>N7</td>
<td>![Symbol for Ra 1.6]</td>
</tr>
<tr>
<td>0.8</td>
<td>N6</td>
<td>![Symbol for Ra 0.8]</td>
</tr>
<tr>
<td>0.4</td>
<td>N5</td>
<td>![Symbol for Ra 0.4]</td>
</tr>
<tr>
<td>0.2</td>
<td>N4</td>
<td>![Symbol for Ra 0.2]</td>
</tr>
<tr>
<td>0.1</td>
<td>N3</td>
<td>![Symbol for Ra 0.1]</td>
</tr>
<tr>
<td>0.05</td>
<td>N2</td>
<td>![Symbol for Ra 0.05]</td>
</tr>
<tr>
<td>0.025</td>
<td>N1</td>
<td>![Symbol for Ra 0.025]</td>
</tr>
</tbody>
</table>

Jigar Talati, Hexagon Design Centre
Direction of 2D measurement

3D view of grounded Sample

2D view of grounded Sample
Direction of 2D measurement

Perpendicular to grinding direction (Ra = 0.690 μm)

At some angle to grinding direction (Ra = 0.426 μm)

Parallel to grinding direction (Ra = 0.133 μm)

Graham Smith, Industrial Metrology, Springer
3D Measuring methodology

3D technique
- Non-contact / contact type
- Areal roughness measurement (areal method type)
- Acquires an area of the surface
- Confocal microscopy, interferometer, atomic force microscopy, etc.

✓ Surface’s waviness
✓ Micro-roughness
✓ Wear ability
✓ Lubricant retention
✓ Angular direction of machining marks
✓ and much more

Noise in 3D measurement

Deep valley
Noise in 3D measurement

High peak

Very fine finish???
Threshold (noise correction of peak and valley)

ISO 4287
Amplitude parameters

- \( R_z \): 3.874 \( \mu m \)
- \( R_t \): 12.966 \( \mu m \)
- \( R_a \): 0.618 \( \mu m \)

ISO 4287
Amplitude parameters

- \( R_z \): 3.454 \( \mu m \)
- \( R_t \): 3.950 \( \mu m \)
- \( R_a \): 0.611 \( \mu m \)

Thresholds

<table>
<thead>
<tr>
<th>Height / Depth</th>
<th>Material ratio</th>
<th>Height</th>
<th>Depth</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.851 ( \mu m )</td>
<td>0.015</td>
<td>0.015%</td>
<td>-2.133 ( \mu m )</td>
<td>98.51%</td>
</tr>
</tbody>
</table>
Material / bearing ratio curve or Abbot-Firestone curve

- It represents the profile as a function of level.
- Plateau honing is often described as cutting off the peaks of a rough honed surface to produce a “worn in” surface.
- 1st operation → obtain a somewhat coarse finish
- 2nd operation → improve the finish by removing surface peaks but often leaves any deep valleys intact.
- It leads to a surface texture type that is often termed a stratified surface.
Understanding vertical scaling
Spatial frequency relation with figure and roughness

Surface form error falls into one of three overlapping categories. Each category represents a portion of the spatial frequency domain.

Brandon Light, Role of Surface Roughness In Optical Performance, Optimax Systems, Inc. 2011
Richard et al., Specification and Control of Mid-Spatial Frequency Wavefront Errors in Optical Systems
Instrument requirements for spatial frequency

- Metrology devices are only useful for a given spatial regime.
- Multiple devices with overlapping spatial regimes may be necessary to fully characterize the roughness.

Regina Soufl, Surface metrology and polishing techniques for current and future-generation EUVL optics, 2011 International Workshop on EUV Lithography, Maui, Hawaii