Roughness Measurements with InfiniteFocus

Pilsen, 18.10.2012
INTRODUCTION OPTICAL ROUGHNESS MEASUREMENT
General Terms
Definitions

» **Form**
  → geometric basic shapes

» **Roughness**
  → high frequency wave length

» **Waviness**
  → low frequency wave length

» **Filtering**
  → the process of separating roughness and waviness
Form – Waviness – Roughness

Raw profile

Primary profile

Waviness profile

Roughness profile

Form profile
# Form and Roughness Measurement

<table>
<thead>
<tr>
<th>Form</th>
<th>Roughness</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Form Diagram" /></td>
<td><img src="image" alt="Roughness Diagram" /></td>
</tr>
</tbody>
</table>

- **CMM measurement points**

## Coordinate measurement device

- **Profilometer**

**IFM combines roughness and form**
Typical Characteristics of Devices under Test for Roughness Measurements

» not transparent
» locally rough (hence they posses local „nano-roughness“)
» typical materials (metal, synthetic, ..)
» often: appropriate flanks
  --> Large scan range
  --> Large working distance necessary
Roughness Profile

Nano-Roughness

- superimposes the significant roughness
- influences the measurability of optical measuring instruments significantly
Methods to Evaluate if the Roughness Measurement is Correct

Possible Methods

» MSA (Measurement System Analysis: Method 1-6)
» GUM (Guide to the expression of Uncertainty in Measurement)
» Gage R&R Study
» ...

All these methods use calibrated comparison standards to demonstrate that a measurement device is capable of measuring a specimen.
Agenda

1. Focus-Variation explained
2. Why does focus variation work for roughness measurement
3. Why does the InfiniteFocus work for roughness measurement
4. Traceability and calibration
5. Practical results
6. Optical versus Tactile
7. Classification
1. Focus Variation and InfiniteFocus Explained
Focus-Variation as Measurement Technique
Focus-Variation Technical Specifications

Optical 3D-surface metrology based on a color focus sensor

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical resolution</td>
<td>&gt;10nm</td>
</tr>
<tr>
<td>Lateral resolution</td>
<td>&gt;400nm</td>
</tr>
<tr>
<td>Scan height</td>
<td>&lt;22mm</td>
</tr>
<tr>
<td>Scan area</td>
<td>100mm x 100mm</td>
</tr>
</tbody>
</table>

Surface measurements in less than 16 sec.
(2 million measurement points, 11.6Mb)
Benefits of Focus-Variation

Form and roughness in one measurement

- Rough and smooth surfaces
- Color information
- Steep flanks
- Diversity of materials
- Large measurement areas
Technology Focus - Variation

Form & Roughness
2.
Why does Focus-Variation work for roughness measurement?
Roughness Performance

» Ra of down to 0.05µm traceable and repeatable
» Measurement range beyond the typical piezo travel range
» Vertical resolution of 10nm
» Lateral resolution of less than 1µm
» Capable of measuring steep slope
» Capable of handling various materials through smart flash and polarization

» These are sales arguments and specs, why do we achieve those?
What we use and what we take care of

» Granite sensor basis
» 2nm glass scale
» Stage with high quality, low flatness and straightness, pitch and yaw
» Specially designed optics
» Low noise, high resolution, high speed CCD sensor
» Minimized temperature contribution
» Optimized vibration isolation
» High effort on system adjustment and calibration utilizing PTB and DKD standards
Why can roughness be measured with Focus-Variation?

11 year of effort with now 28 people in R&D with competence in:

» 5 PhD, 18 Masters,...
» 6 year of work in ISO, VDI and ÖNORM
» Strong cooperation with NPL and PTB
» Competence in optics, metrology, mathematic, software development, computer vision
Why does Focus-Variation work for roughness measurement?

Focus-Variation works if:
- lateral and vertical resolution of measurement is sufficiently smaller than the relevant lateral and vertical structures of the sample.

Nano roughness cannot be resolved BUT the lateral structure can be resolved!
Why does Focus-Variation work for roughness measurements?

Since the human eye can distinguish sharp and unsharp areas the system can as well.
3. Why does the InfiniteFocus work for roughness measurement?
Advantages of InfiniteFocus for Roughness Measurement

» Measurement of small structures
  example: IF-RoughnessTool100

» Measurement of samples with small random structures
  example: Random Roughness Standard

» Large scan height > 400µm possible
  example: applicable samples

» Large working distance possible
  example: injection nozzle, tap - nut
MEASUREMENT OF SMALL STRUCTURES
IF-RoughnessTool100
Problem

Often small roughness (e.g. 100nm) on small samples with very small lateral structures (<10µm) have to be measured.

The measurement device must possess a small lateral and vertical resolution.

Example:

periodical roughness standard IF-RoughnessTool100

Solution: InfiniteFocus has a lateral resolution < 1µm and a vertical resolution of 10nm
Example: IF-RoughnessTool100
IF-RoughnessTool100

Ra: 100.27nm
Measurable Lateral Structures

5 µm structures can be measured efficiently (without error)
→ also smaller structures (~1 µm)
MEASUREMENT WITH SMALL REAL (RANDOM) STRUCTURES
Random Roughness Standard
Problem

Nearly all real samples have small/random structures.

Example:
- precision components
- milled parts
- roughness standard with random structure

Solution:
InfiniteFocus has a small lateral resolution.

Evidence:
Comparison of a Focus-Variation measurement with a tactile measurement device on a random DKD calibrated roughness standard
3D Measurement of a Roughness Standard with Random Structure

3D Measurement InfiniteFocus

used roughness standard
manufacturer: Rubert, UK
structure: random
length: 4 x 1.25mm
Profile Comparison: Tactile - InfiniteFocus

true colour picture with profile path

profile InfiniteFocus

profile tactile measurement device (not at the same position as above)

How good is the correlation of the two profiles?
Accomplishment Profile Comparison

» Superimpose two tactile measurements on different positions
  → allows estimations of homogeneity of the tools

» Superimpose tactile and InfiniteFocus measurements
  → allows estimations of correlation between optical and tactile measurement

» Calculation of the correlation for a quantification
Profile Comparison

comparison of 2 tactile measurements: correlation 0.68

The red profile is identical in both diagrams

comparison of tactile (red) and InfiniteFocus measurement (green): correlation 0.84

6µm (valley to peak)

The red profile is identical in both diagrams
Interpretation of the Profile Comparison

» Both tactile profiles show some deviations
  --> The tool is not completely homogeneous.
  --> There are artefacts (dust, ..) visible on the tool

» The graphs tactile/optical do coincide better than tactile/tactile
  --> Hence there is a very good correlation between optical and tactile measurement. The influence of the sample is much more evident than the influence of the measurement device.

The correlation of tactile/tactile measurements (0.68) is less than tactile/optical (0.84).
**Comparison of the Ra Values**

**Optical – Tactile Device**

<table>
<thead>
<tr>
<th></th>
<th>tactile system (9 positions)</th>
<th>InfiniteFocus (10 positions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>average Ra</td>
<td>120</td>
<td>121</td>
</tr>
<tr>
<td>min Ra</td>
<td>120</td>
<td>118</td>
</tr>
<tr>
<td>max Ra</td>
<td>130</td>
<td>124</td>
</tr>
<tr>
<td>repeatability</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

*Measurement length: 1.25mm*

*Lc: 0.25mm*

*Tactile stylus radius: 2µm*

*Lateral resolution InfiniteFocus: 0.9µm*

*Used objective: 100x*
LARGE SCAN RANGES >400µm POSSIBLE
inclined samples
Example: Roughness Measurement of the Thread

Scan height: 1.4mm

Roughness measurement on the flank

Roughness measurement on the root of the thread

Ra: 766.800946 nm

Ra: 449.445505 nm
Problem

Measurement of roughness over large vertical scan ranges

Example:
» measurement of roughness on inclined surfaces
» measurement of roughness on the thread and in the flute
» measurement of roughness on precision components with declined surfaces

Solution:
» InfiniteFocus enables measurements up to approx. ~85°
» InfiniteFocus has scan ranges up to 22mm

Evidence:
measurement of the IF-RoughnessTool500 at different inclinations
Roughness Measurement on Inclined Surfaces with Scan Ranges > 400µm

Example: roughness measurement in the flute and at the thread

Sa 9.97µm
Example: Roughness Measurement on Inclined Surfaces with Scan Ranges > 400µm

IF-RoughnessTool500 measured at an angle of 45°

IF-RoughnessTool500 reference-plane adjusted
Maximum Tilt Angle and Other Instruments

Example confocal:
10x objective: FOV: 1600µm
Scan z = 250µm
→ limited by vertical scan range
Maximum Angle = atan(250/1600)= 8.8°
(limitation so that the full field of view can be used for Sx calculation)

Example WLI:
10x objective, NA = 0.3
→ Limited by numerical aperture
Maximum angle = asin (0.3) = 17°
IF-RoughnessTool500: Measured Ra Values at Different Sample Inclinations

Roughness can be measured on steep flanks

<table>
<thead>
<tr>
<th>Sample inclination [°]</th>
<th>Measured Ra in µm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>tacticle system (12 positions, all at 0°)</td>
</tr>
<tr>
<td>Average Ra</td>
<td>495</td>
</tr>
<tr>
<td>Min</td>
<td>491</td>
</tr>
<tr>
<td>Max</td>
<td>499</td>
</tr>
</tbody>
</table>
## Roughness Measurement on an Inclined Roughened Gage Block

<table>
<thead>
<tr>
<th>Tilt</th>
<th>Sa [nm]</th>
<th>Sq [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>136.21</td>
<td>171.01</td>
</tr>
<tr>
<td>10°</td>
<td>129.22</td>
<td>164.43</td>
</tr>
<tr>
<td>20°</td>
<td>155.25</td>
<td>206.19</td>
</tr>
<tr>
<td>30°</td>
<td>177.11</td>
<td>226.43</td>
</tr>
<tr>
<td>40°</td>
<td>269.04</td>
<td>339.17</td>
</tr>
</tbody>
</table>

Measured Sa/Sq in µm

![Sa Measurement on Tilted Surface [nm]](chart.png)

- **Measured Sa**
- **+Uncertainty**
- **-Uncertainty**

**Consistent results**
LARGE WORKING DISTANCE POSSIBLE

injection nozzles, tap-nut
Problem

*Measurement of roughness at position which requires a large working distance*

Examples:

» Injection nozzles
» Flute of a tap
» Root of threads from implants
» Diverse precision components

Solution:

*InfiniteFocus allows working distances up to 23.5 mm*
Large Working Distance

Problem:
Many measurement devices do not support measurement with large working distances.

But this is necessary in many sectors!

Examples:
» injection nozzles
» roughness in the flute of tools
» micro precision components
# Working Distances InfiniteFocus

<table>
<thead>
<tr>
<th>Objectives</th>
<th>2.5x</th>
<th>5x</th>
<th>10x</th>
<th>20x</th>
<th>50x</th>
<th>100x</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.8mm</td>
<td>23.5mm</td>
<td>17.5mm</td>
<td>13.0mm</td>
<td>10.1mm</td>
<td>3.5mm</td>
</tr>
</tbody>
</table>

![Working distance](image-url)
4. TRACEABILITY AND CALIBRATION

Based on Focus-Variation
Traceability of Profile Roughness Measurements

Profile Roughness Measurement:
» Profile standard
» ISO 4287,…
» DAkkS (DKD) Lab
» PTB 5.1

Complete traceability given
Traceability of Surface Texture Measurements

Surface Texture Measurement:

» Surface standard:
  In work (PTB, Japan)

» ISO 25178-x
  Not yet finished

» DAkkS Labs
  Not available

» PTB 5.1 / OpenGPS
  Not yet defined

No complete chain

This does not mean that areal based roughness measurements may not be used!
Available Roughness Standards are too Smooth & Specular

» no local nano-roughness: shiny surface, hard to measure for optical instruments
» roughness of the standard: produced by sine wave form
IF-RoughnessTool Optimized for Optical Measurement

significant local nano-roughness: well measureable by optical and by tactile instruments

» roughness of the standard: mainly produced by sine wave form
Tactile Roughness Standard

Practical roughness standard:

Local roughness of this standard (using a small Lc):

In this case the local roughness represents the form error of the standard
Local roughness of this standard (using a small Lc):

InfiniteFocus can measure the standard well if: Ra (Sa) of this local roughness is above 10-15nm
IF-RoughnessTool

Problem:
Traceable roughness measurements were not possible because there was no measurable roughness standard available.

Solution:
IF-RoughnessTool

Roughness values: Ra: 100nm, 500nm, 1500nm, 3000nm
IF-RoughnessTool Measurement

Delivered with DKD Certificate!

Objective: 50x, vertical resolution: 50nm, ImageField10x1
Profile Roughness

Profile Path

Extracted Profile

$\lambda_c: 250\mu m$
Example: Result IF-RoughnessTool100

<table>
<thead>
<tr>
<th></th>
<th>tactile system</th>
<th>InfiniteFocus</th>
</tr>
</thead>
<tbody>
<tr>
<td>average Ra</td>
<td>97nm</td>
<td>105nm</td>
</tr>
<tr>
<td>uncertainty</td>
<td>+-5nm</td>
<td>+-20nm</td>
</tr>
<tr>
<td>repeatablity</td>
<td>2nm</td>
<td>1nm</td>
</tr>
</tbody>
</table>

» InfiniteFocus is comparable with tactile measurements
» InfiniteFocus has a better repeatability
» InfiniteFocus has a „worse“ uncertainty:

\[ U_{IFM} = U_{Taktıl} + X \]

(the uncertainty of the InfiniteFocus is currently based on tactile measurement, including it)
**Example: Results IF-RoughnessTool500**

<table>
<thead>
<tr>
<th></th>
<th>Tactile system</th>
<th>InfiniteFocus</th>
</tr>
</thead>
<tbody>
<tr>
<td>average Ra</td>
<td>503.5nm</td>
<td>501.3nm</td>
</tr>
<tr>
<td>uncertainty</td>
<td>+-15nm</td>
<td>+-40nm</td>
</tr>
<tr>
<td>repeatability</td>
<td>5nm</td>
<td>1nm</td>
</tr>
</tbody>
</table>
Example: Result IF-RoughnessTool3000

<table>
<thead>
<tr>
<th></th>
<th>Tactile system</th>
<th>InfiniteFocus</th>
</tr>
</thead>
<tbody>
<tr>
<td>average Ra</td>
<td>2977nm</td>
<td>3023 nm</td>
</tr>
<tr>
<td>uncertainty</td>
<td>+-90nm</td>
<td>+-250nm</td>
</tr>
<tr>
<td>repeatability</td>
<td>5nm</td>
<td>8nm</td>
</tr>
</tbody>
</table>
# Overview Roughness Measurements with Standards

<table>
<thead>
<tr>
<th>Nominal Ra</th>
<th>120</th>
<th>100</th>
<th>500</th>
<th>3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>random</td>
<td>sinus</td>
<td>sinus</td>
<td>sinus</td>
</tr>
<tr>
<td>Mean deviation (optical-tactile)</td>
<td>5</td>
<td>5</td>
<td>15</td>
<td>80</td>
</tr>
<tr>
<td>Repeatability tactile</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Repeatability optical</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Uncertainty tactile (Ut)</td>
<td>4</td>
<td>10</td>
<td>15</td>
<td>90</td>
</tr>
<tr>
<td>Uncertainty optical (Uo)</td>
<td>20</td>
<td>25</td>
<td>40</td>
<td>250</td>
</tr>
</tbody>
</table>

(values in nm)

The uncertainty optical $U_o$ „includes“ the uncertainty tactile $U_t$.
Overview Roughness Measurements

Typical values for Ra measurements with real samples at different Ra ranges

<table>
<thead>
<tr>
<th>Roughness range Ra</th>
<th>50-200nm</th>
<th>200-700nm</th>
<th>700-3000nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeatability</td>
<td>5nm</td>
<td>5nm</td>
<td>15nm</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>25nm</td>
<td>50nm</td>
<td>300nm</td>
</tr>
<tr>
<td>Max. measurable angle range</td>
<td>30°-50°</td>
<td>20°-50°</td>
<td>10°-50°</td>
</tr>
</tbody>
</table>

Depending on the surface composition of the samples the stated values can deviate. The measureable angle range depends on the gradient of the surface (e.g.: Rdq parameter)

InfiniteFocus measurement uncertainty is dominated by the uncertainty of the reference measurement.

**Improvement of optical measurement devices by:**
- reduction of the uncertainty of DKD and PTB
Roughness Standards

calibrated roughness standards
» structure is measured with a reference measurement device
  → roughness value for the certificate
» assures reference to national standards
» assures reproducibility with other measurement devices

Institutions for calibration
» DAkkS (prior DKD)
» PTB
» NIST
Standards for Roughness Measurements

Two types of standards:
- periodical roughness standards
- random roughness standards

*Roughness standard have to be practice oriented*
- similar characteristics as the work piece* to be measured
- locally rough (hence a certain nano-roughness)
- similar Ra value as the work piece to be measured
- similar optical characteristics as the work piece to be measured

Nano-roughness influences significantly the measurability

*analogous requirements are valid for dimensional measurements:
ISO 15530-3: Coordinate measurement machines (CMM): Technique for determining the uncertainty of measurement – Part 3: Use of calibrated workpieces or standards. Section 5.2: Similarity Conditions*
Typical Problems of Measurements with Roughness Standards

» The roughness standard is not applicable for every measurement technology.
   - The measurement is not ideal
   - The roughness measurement is far away from the calibrated value

Example: Usage of very smooth roughness standards for optical roughness measurements.

» **Not the same measurement position** is used for tactile and optical measurement.

» **Not the same measurement setting** are used (filter settings, duration of the measurement).
5.

Practical Examples
Example 1: Measurement of Injection Nozzles

1. High resolution 3D measurement of the entire sealing face
2. Removal of the bevelled form
3. Calculation of the flatness parameter FLTt according to ISO 12781
Example 1: Measurement of Injection Nozzles

Measurements on the Sealing surface possible

3D measurement of the sealing surface
Measurement Task

Is the fuel supply with closed valve interrupted?

Boundary conditions: multiple injections of lowest quantities, pressures up to 2000 bar

sealed?
Flatness – Visualized After Form Removal

**flatness**

**FLTt**: 3.2273μm
Roundness/ Leak Tightness

Leakage

Leakage
Repeatability of Roundness Measurement

Repeatability of roundness measurements
Based on 20 measurements

|     | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   | 14   | 15   | 16   | 17   | 18   | 19   | 20   | Standard-deviation |
|-----|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|-------------------|
| RONa| 0.630| 0.633| 0.653| 0.567| 0.629| 0.603| 0.753| 0.654| 0.611| 0.637| 0.676| 0.677| 0.531| 0.683| 0.640| 0.648| 0.584| 0.606| 0.630| 0.049            |
| RONq| 0.781| 0.791| 0.806| 0.716| 0.780| 0.755| 0.923| 0.803| 0.753| 0.790| 0.842| 0.853| 0.724| 0.704| 0.847| 0.807| 0.804| 0.735| 0.764| 0.777| 0.053            |
| RONp| 2.124| 2.220| 2.388| 2.159| 2.283| 2.287| 2.363| 2.267| 2.151| 2.566| 2.535| 2.555| 2.276| 2.470| 2.413| 2.570| 2.348| 2.221| 2.190| 2.222| 0.146            |
| RONv| 1.715| 1.615| 1.929| 1.843| 1.955| 1.944| 1.747| 1.880| 1.669| 1.991| 1.979| 1.953| 1.911| 2.247| 1.838| 2.122| 1.578| 1.834| 1.940| 1.818| 0.162            |

(values in µm)
High Resolution 3D Measurement
Form Reduced Datasets
Dataset after Filtering
Roughness Parameters

Surface Texture of Roughness Dataset

<table>
<thead>
<tr>
<th>Settings</th>
<th>Min. Value</th>
<th>Max. Value</th>
<th>Class Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>-2.5759 μm</td>
<td>4.8351 μm</td>
<td>0.06 μm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Name</th>
<th>Value</th>
<th>[a]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Elements</td>
<td>1906216</td>
<td></td>
<td>Number of data values</td>
</tr>
<tr>
<td></td>
<td>Classes</td>
<td>149</td>
<td></td>
<td>Number of histogram classes</td>
</tr>
<tr>
<td></td>
<td>Mean Value</td>
<td>0.0139 μm</td>
<td></td>
<td>Mean value of data values</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>0.4345 μm</td>
<td></td>
<td>Mean Value of standard deviation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Selected Class</th>
<th>Name</th>
<th>Value</th>
<th>[a]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Class Index</td>
<td>-</td>
<td></td>
<td>Index of selected class</td>
</tr>
<tr>
<td></td>
<td>Percentage</td>
<td>- %</td>
<td></td>
<td>Percentage of data in selected class</td>
</tr>
<tr>
<td></td>
<td>Lower Border</td>
<td>- μm</td>
<td></td>
<td>Lower class limit</td>
</tr>
<tr>
<td></td>
<td>Upper Border</td>
<td>- μm</td>
<td></td>
<td>Upper class limit</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Name</th>
<th>Value</th>
<th>[a]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sa</td>
<td>347.06</td>
<td></td>
<td>Average height of selected area</td>
</tr>
<tr>
<td></td>
<td>Sq</td>
<td>494.73</td>
<td></td>
<td>Root-Mean-Square height of selected area</td>
</tr>
<tr>
<td></td>
<td>Sp</td>
<td>4.8351 μm</td>
<td></td>
<td>Maximum peak height of selected area</td>
</tr>
<tr>
<td></td>
<td>Sv</td>
<td>2.5759 μm</td>
<td></td>
<td>Maximum valley depth of selected area</td>
</tr>
<tr>
<td></td>
<td>Sz</td>
<td>7.4223 μm</td>
<td></td>
<td>Maximum height of selected area</td>
</tr>
<tr>
<td></td>
<td>S10z</td>
<td>2.9679 μm</td>
<td></td>
<td>Ten point height of selected area</td>
</tr>
<tr>
<td></td>
<td>Skk</td>
<td>-0.56888</td>
<td></td>
<td>Skewness of selected area</td>
</tr>
<tr>
<td></td>
<td>Sku</td>
<td>2.9415</td>
<td></td>
<td>Kurtois of selected area</td>
</tr>
<tr>
<td></td>
<td>Sqg</td>
<td>0.2742</td>
<td></td>
<td>Root mean square gradient</td>
</tr>
<tr>
<td></td>
<td>Sdr</td>
<td>3.5126</td>
<td>%</td>
<td>Developed interfacial area ratio</td>
</tr>
<tr>
<td></td>
<td>FLTt</td>
<td>7.4223 μm</td>
<td></td>
<td>Flatness using least squares reference plane</td>
</tr>
<tr>
<td></td>
<td>Lc</td>
<td>80 μm</td>
<td></td>
<td>LambdaC: cutoff wavelength</td>
</tr>
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</table>
# Repeatability Roughness Measurement

<table>
<thead>
<tr>
<th></th>
<th>Measurement 1</th>
<th>Measurement 2</th>
<th>Measurement 3</th>
<th>Measurement 4</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sa</td>
<td>0.329</td>
<td>0.329</td>
<td>0.329</td>
<td>0.328</td>
<td>0</td>
</tr>
<tr>
<td>Sq</td>
<td>0.460</td>
<td>0.459</td>
<td>0.458</td>
<td>0.458</td>
<td>0.001</td>
</tr>
<tr>
<td>Sz</td>
<td>14.33</td>
<td>12.39</td>
<td>14.1</td>
<td>14.2</td>
<td>0.915</td>
</tr>
<tr>
<td>Sp</td>
<td>11.63</td>
<td>9.389</td>
<td>11.73</td>
<td>11.31</td>
<td>1.098</td>
</tr>
<tr>
<td>Sv</td>
<td>2.706</td>
<td>3.003</td>
<td>2.369</td>
<td>2.885</td>
<td>0.276</td>
</tr>
<tr>
<td>Ssk</td>
<td>2.871</td>
<td>2.708</td>
<td>2.694</td>
<td>2.788</td>
<td>0.081</td>
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<tr>
<td>Sku</td>
<td>48.69</td>
<td>44.55</td>
<td>45.23</td>
<td>47.76</td>
<td>1.982</td>
</tr>
<tr>
<td>Sdq</td>
<td>2.67</td>
<td>2.6</td>
<td>2.639</td>
<td>2.608</td>
<td>0.031</td>
</tr>
<tr>
<td>Sdr</td>
<td>3.092</td>
<td>2.985</td>
<td>3.031</td>
<td>3.038</td>
<td>0.043</td>
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<tr>
<td>S10z</td>
<td>11.47</td>
<td>9.654</td>
<td>10.62</td>
<td>11.75</td>
<td>0.944</td>
</tr>
</tbody>
</table>

[values in µm]
Example 2: How can printability be quantified?

Good printability

Poor printability

Calculation of roughness parameters

Images from UPM
Calculation of Roughness Parameters

Measurement

Form-Removal

Measurement module selection?

Profile measurement

Lc selection

Parameter-calculation

Areal measurement

Lc selection

Parameter-calculation

Typical parameters
- Sa
- Spk
- Sk
- Svk
- ftol
Measurement of the Topography
Roughness Measurement - Removing Waviness

Original measurement

After filtering out waviness
Profile Roughness/Area Roughness

Profile Roughness

Ra 8.27µm

Area Roughness

Sa 9.18µm
Comparison of Printability

Good printability

Poor printability
Roughness Measurement: Amplitude Parameter

**Good printability**

Sa = 0.693µm

**Poor printability**

Sa = 4.281µm
Roughness Measurement: Material Area Curve

Good printability

Sk = 2.0434µm

Poor printability

Sk = 13.416µm
Example 3: Surgeries for a Broken Bone

Broken Bone

1\textsuperscript{st} Surgery

*Place the implants*

2\textsuperscript{nd} Surgery

*Remove the implants*
Cooperation project

Project: “BioResorable Implants for Children”

Study of implants made of Mg-Ca-Zn that dissolve in time inside the body and do not need removal surgery; surface of implants has been measured before and after 8 weeks while they were placed inside biological body (rats)
Aim

Find the **correlation between surface and biological behavior**
Measurement Challenge

» Rugged surface
» Various materials
» Non destructive measurements
» Repeatable and traceable measurements required
Solution for the Future

Bioresonable implants

Visualization of the bone implant

3D measurement of an implant
Important for the Roughness Measurement of Implants:

Remove the cylindrical form

Removing the cylindrical form makes roughness measurements repeatable
Step 1: Measure the Implants

3 different materials were examined

Magox
(LV1 alloy)

WZ21
(crystalline magnesium alloy
Mg, 1% Zn, 0.25% Ca,
0.15%Mn, 2% Yttrium)

LU1
(crystalline magnesium alloy
Mg, 5% Zn, 0.25% Ca,
0.15%Mn)
# Material Comparison

## Parameter Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Material 1</th>
<th>Material 2</th>
<th>Material 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Magox</td>
<td>WZ21</td>
<td>LU1</td>
</tr>
<tr>
<td><strong>Sa</strong></td>
<td>1.32 µm</td>
<td>0.19 µm</td>
<td>0.12 µm</td>
</tr>
<tr>
<td><strong>Sq</strong></td>
<td>1.85 µm</td>
<td>0.25 µm</td>
<td>0.15 µm</td>
</tr>
<tr>
<td><strong>Sz</strong></td>
<td>25.12 µm</td>
<td>2.33 µm</td>
<td>1.87 µm</td>
</tr>
<tr>
<td><strong>Lc</strong></td>
<td>200µm</td>
<td>200µm</td>
<td>200µm</td>
</tr>
</tbody>
</table>

- **Largest roughness values**
- **Still contains waviness**
6.
Optical versus Tactile
Introduction to Tactile Instruments

A tactile instrument measures the contact between the tactile tip and the specimen surface. Through moving the tip over the surface a profile or area is measured.
Introduction to Tactile Instruments

The stylus tip is not sharp but round:

The tip is NOT measuring the surface but the contact points of the tip and the surface.
Problems of Tactile Instruments

1. Machining traces
2. Measuring traces
3. Si-crystall (hard)
4. Al-matrix (soft)
5. Deviation of the stylus tip

The tip is generating a groove
The tip is deflected

Images courtesy by Prof. Dr.-Ing. Jörg Seewig, Techn. Univ. Kaiserslautern, Germany
Problems of Tactile Instruments

- Slipping effect
- Bouncing effect
- Material deformation caused by tip
- Less informative (single profile)
- Tip wear
- User does not know where the profile was measured
- Limited vertical scan range
- Often only roughness can be measured
- No steep flanks possible
Problems of Optical Instruments

- Most available roughness standards are too smooth and specular for optical systems
- Some optical devices (e.g. white light interferometers) are not optimal for certain roughness measurements
Problems of White-Light-Interferometry

- Deviation of WLI Ra values from calibrated values
  - Blue: Random roughness specimen
  - Pink: Sinusoidal gratings

- Deviations of the Ra measurements are very high.
- Up to 100% of the nominal value!
- Especially in the range Ra > 50 and Ra < 300nm

Figure taken from
Theoretical Comparison

Differences at different scales:

» Big measurement values: mm range
  very small differences, depending on application

» Medium measurement values: µm range
  Depending on surface roughness and material differences can occur

» Small measurement values: nm range
  Large differences expected
Problems when Comparing Optical and Tactile Instruments

Problems of Tactile Instruments
» Size and form of stylus tip influences measurement result
» Interaction of stylus tip is complex to understand

Problems of Optical Instruments
» Tactile roughness standards are often too smooth
» Some optical systems (e.g. white light interferometers) are not optimal for certain roughness measurements

Problems of the Comparison Procedure
» It is difficult to find the same measurement position
» International standards are not completely unambiguous
  → different software gives different results on the same profile
Problems of Comparisons

» Correct measurement position

» Structure of roughness standard and part nearly equal!

» Tactile or optical, which is more accurate? (especially on random roughness specimens)

» International standards are not completely unambiguous

→ Different software gives slightly different results on the same profile.
Advantages of optical instruments

- Typically at total area is measured
- More data points are measured in less time
- More data points allow filtering surface and surface parameters
- No contact with the sample. This means no wear on the surface.
- True color information
Advantages of InfiniteFocus
Compared to Tactile Measurements

Advantages of InfiniteFocus over a profilometer:
» IFM can measure areas instead of profiles
» IFM can measure form and roughness at once
» IFM has got a high vertical scan range
» IFM uses color information to know where you are measuring
» You can measure elastic materials
» You can measure very rough surfaces and surfaces with slopes reliably
» High lateral sampling
» High lateral resolution
» Less maintainence (no stylus tip replacement)
» Very flexible measurement options
» Not only for flat samples
Profile versus Surface
Examples where to use Profile or Area Measurement

Profile Measurement

» Surfaces with structure in one direction and no structure in the other direction (for example: turned surfaces)
» Roughness measurement that must be comparable with tactile instruments

Area Measurement

» Measuring the flatness of a surface
» Measuring the roughness of structured surfaces with complex forms (eg. paper)
» Surfaces with random surface texture
» Measurement of complex parameters
Area Versus Profile Measurement

Profile Measurement gives only limited information
» You have to know your surface and what you are doing
» Area Measurement can help obtaining more reliable results

Extracted profile:

Same profile but completely different surface structure
Area Measurement Advantages

» More repeatable results
» More complex parameters are possible
» More significant parameters (volume parameters,...)
» Less user influence
» Much more parameters are possible (fractal dimension, autocorrelation, local homogeneity, gradient distribution)
Roughness Parameters

The average roughness, $R_a$, is an integral of the absolute value of the roughness profile. It is the shaded area divided by the evaluation length, $L$. $R_a$ is the most commonly used roughness parameter.

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

$$R_q = \frac{1}{L} \int_0^L Z^2(x) \, dx$$

$Z(x)$ = profile ordinates of roughness profile
Rz – Rmax – Rt

Rz = Mean value of Z1, Z2, Z3, Z4, Z5

Rt
Maximum peak to valley height of the roughness profile

Rmax
Maximum peak to valley height of the roughness profile within a sampling length

Rz
Average peak to valley height of the roughness profile
VDI Roughness Method

The VDI Roughness Method is a very old method, seldom used.

VDI Roughness = 20*\lg(10*Ra)

<table>
<thead>
<tr>
<th>VDI/ISO</th>
<th>Ra (\mu m)</th>
<th>\text{n}inch</th>
<th>N3-N10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-6.5</td>
<td>0.1 - 4.4</td>
<td>0.022 - 0.15</td>
<td></td>
</tr>
<tr>
<td>7-10</td>
<td>0.16 - 6.4</td>
<td>0.22 - 1.0</td>
<td></td>
</tr>
<tr>
<td>11-14</td>
<td>0.18 - 7.2</td>
<td>0.25 - 1.2</td>
<td></td>
</tr>
<tr>
<td>15-18</td>
<td>0.2 - 9</td>
<td>0.28 - 1.1</td>
<td></td>
</tr>
<tr>
<td>19-22</td>
<td>0.3 - 14</td>
<td>0.32 - 12.8</td>
<td></td>
</tr>
<tr>
<td>23-26</td>
<td>0.4 - 24</td>
<td>0.45 - 18</td>
<td></td>
</tr>
<tr>
<td>27-30</td>
<td>0.5 - 32</td>
<td>0.5 - 20</td>
<td></td>
</tr>
<tr>
<td>31-34</td>
<td>0.6 - 40</td>
<td>0.6 - 36</td>
<td></td>
</tr>
<tr>
<td>35-38</td>
<td>1.0 - 50</td>
<td>1.2 - 44.8</td>
<td></td>
</tr>
<tr>
<td>39-42</td>
<td>1.6 - 63</td>
<td>1.6 - 56</td>
<td></td>
</tr>
<tr>
<td>43-46</td>
<td>2.2 - 88</td>
<td>2.2 - 56</td>
<td></td>
</tr>
<tr>
<td>47-50</td>
<td>2.8 - 112</td>
<td>2.8 - 56</td>
<td></td>
</tr>
<tr>
<td>51-54</td>
<td>3.2 - 140</td>
<td>3.2 - 56</td>
<td></td>
</tr>
<tr>
<td>55-58</td>
<td>4.5 - 180</td>
<td>4.5 - 56</td>
<td></td>
</tr>
<tr>
<td>59-62</td>
<td>6.0 - 280</td>
<td>6.0 - 56</td>
<td></td>
</tr>
<tr>
<td>63-66</td>
<td>8.0 - 500</td>
<td>8.0 - 56</td>
<td></td>
</tr>
<tr>
<td>67-70</td>
<td>10.0 - 650</td>
<td>10.0 - 56</td>
<td></td>
</tr>
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<td>71-74</td>
<td>12.5 - 650</td>
<td>12.5 - 56</td>
<td></td>
</tr>
<tr>
<td>75-78</td>
<td>16.0 - 650</td>
<td>16.0 - 56</td>
<td></td>
</tr>
</tbody>
</table>
Sdr – Developed interfacial area ratio

Example 1 – **Sdr: 250%**

Example 2 – **Sdr: 40%**
Bearing Area Curve Parameters

- are based on the bearing area ratio curve (Abbot-Firestone)
- includes the Rk family of parameters
Small bearing area: Example: only 4% of the total surface is above the red line

A small bearing area is indicated by a steep slope at the beginning of the bearing area curve.
How are the Parameters Rk, Rvk, Rpk calculated?

1. A line (blue) is fitted into the bearing curve (conform to ISO standards)
2. The intersections of this line and the y-axis are determined.
3. Rk, Mr1 and Mr2 are determined from these intersections.
4. The grey areas define the parameters Rpk and Rvk
Large bearing area: Example: 78% of the total surface is above the red line

A large bearing area is indicated by a small slope at the beginning of the bearing area curve.
Functional or Volume Parameters

Volume parameters are calculated for whole surfaces. For better visualization only a profile through the surface is shown above.
What are Volume Parameters?

- **Vmp**: peak material volume
- **Vmc**: core material volume
- **Vvc**: core void volume
- **Vvv**: valley void volume

Diagram: A graph with the y-axis labeled 'Height' and the x-axis labeled from 0% to 100%. The graph illustrates the distribution of void and material volumes with shaded regions above and below a curve.
When to use Volume Parameters

- **High Vmc:** Voids, low Vvc
- **Low Vmc:** Voids, high Vvc

→ Completely different volume parameters

Volume parameters can distinguish better between surfaces than others. Volume parameters are called functional parameters.
7. Classification
How can surface parameters be quantified by measurement parameters?

Parameter & Surface Characteristic
Classification

What is it?

Classification/Selection is the step of determining the relevant parameters to distinguish good from bad parts.

Why is it important?

1. It helps the user to identify the relevant parameters
2. It helps in classifying unknown parts
Roughness Parameter Selection

Different parameters to characterize the surface:
Sa, Ra, Sdq, Vvc, Sal...

Which parameters should be used for which application?

_Alicona can give hints which parameters can be useful for which application_
Two Different Surfaces – Same Sa, Sq, Sz...

Sa 2.1494µm
Sq 2.4904µm
Sz 13.898µm
...but Different Volume Parameters

- $V_{mp} = 0.0369 \mu m$
- $V_{mc} = 2.8811 \mu m$
- $V_{vc} = 2.1209 \mu m$
- $V_{vv} = 0.2898 \mu m$

- $V_{mp} = 0.1049 \mu m$
- $V_{mc} = 2.0427 \mu m$
- $V_{vc} = 3.8958 \mu m$
- $V_{vv} = 0.0829 \mu m$
Procedure for selecting significant parameters

1. Measure good and bad parts on several positions
2. Optionally …
   a. ...remove form
   b. ...filter out waviness
   c. ...filter out unimportant roughness
3. Measure all parameters from good and bad parts
4. Select significant parameters based on mean and standard deviations
Select Significant Parameters

Is the Parameter Significant:

- Mean of Parameter
- 2*standard deviation of Parameters’ values

The bigger the better

- good part
- bad part

Mean of Parameter
Select Significant Parameters

If this does not work it does not mean that there are no significant parameters.
InfiniteFocus roughness measurements are comparable to tactile roughness measurements.

InfiniteFocus roughness measurements are traceable to national standards.

With InfiniteFocus also roughness on inclined surfaces with large working distance can be measured.
Auxiliary: Overview Lateral

Lateral resolution (3D)

Smallest lateral 3D structure that can be resolved

Too small lateral distance in 3D => cannot be resolved

Cannot be resolved optically (in 2D)

Measured surface
Real surface
Features in optical color image
Measurement point

Optical lateral resolution (2D)

Measurement point distance
Auxiliary: Lateral Resolution and Sampling Distance

[Diagram showing lateral resolution, sampling distance, measured profile, real profile, and integrated depth value]