Understanding the Capabilities of Your Surface Measurement System

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Bruker-Nano History

- 1960: **Bruker Corporation** founded (Karlsruhe, Germany)
- 1962: **Sloan Technology** founded (1986: Acquired by Veeco)
- 2010: **Bruker-Nano** founded (Tucson, Santa Barbara, Camarillo)

**Technology driven**
- Over 180 Patents
  (AFM & Profilers)
- Numerous National Technology Awards

New Bruker-Nano manufacturing facility in Tucson, AZ
Bruker Stylus and Optical Metrology Unit is a Leader in Surface Measurement Innovation

- **Leader in Optical Profiling**
  - World’s first non-contact profiler using phase shifting interferometry
  - World’s first white light profiler
  - World’s first self-calibrating optical Profiler
  - Interferometric, confocal, and bright-field imaging technologies

- **Leader in Stylus Profiling**
  - Over 50 years of the lowest-noise stylus profilers
  - First thin-film capable stylus system
  - First 300mm stylus system
  - First and only quick tip exchange for maximum measurement flexibility

- **More than 8,000 optical and stylus instruments worldwide**

- **More than 40 staff devoted to instrument development and applications**
  - Over 60 patents in Optical and Stylus Measurement Techniques
  - 25% of Tucson development team have doctorate degrees
  - 7 Major industry awards for innovation
Key Drivers Are Encouraging Greater Surface Control

- **Miniaturization**
  - A given tolerance is now a greater percentage of the part dimensions
  - Friction and wear behaviors are different at the micro-scale

- **Outsourcing**
  - Many vendors meet unwritten performance requirements
  - Matching multiple vendors often requires additional specifications

- **Regulatory Improvements**
  - Emissions requirements for transportation
  - Efficiency goals for lighting and appliances
  - Recycling requirements

- **Warranty/Reliability Roadmaps**
  - Expectations of lifetime continually increase

- **Differentiation**
  - Appearance
  - Highest quality product
Key Considerations for Choosing Your Metrology System

- What are you measuring?
  - Part Dimension
  - Feature Size (heights, widths)
  - Roughness
  - Key parameters
  - Dynamic, static, encapsulated?
  - Today, tomorrow...
- How well do you need to measure it?
  - Accuracy
  - Repeatability
  - Gage
- Who will be measuring it?
  - Engineers
  - Skilled operators
  - Multiple unskilled users

- Matching needs
  - Standards (ISO, ASME...)
  - Legacy systems
  - Other metrology systems (vendors, customers, other sites, same site)
- How quickly do you need data?
  - Long term research
  - Failure analysis
  - Production monitoring
Multiple Surface Metrology Technologies Serve Diverse Needs

- **AFM**: Highest lateral resolution with multiple modes and applications
- **3D Microscopy using WLI**: Highest vertical resolution, non-contact high-speed 3D measurements
- **Stylus**: Low noise contact profiling with excellent measurement repeatability

**Atomic Force Microscopy**
Nanoscale characterization of electrical, magnetic, compositional and material properties

**Optical Profiling**
Non-contact 3D measurement of surface texture and roughness

**Stylus Profiling**
Measure thin film step heights, stress and surface texture
Each Metrology Technique Serves Specific Height and Lateral Ranges
Some System Choices Are Simple... But Most Are Not

- No physical access to the part (encapsulated, deeply recessed): 3D Microscope

- Nm-level lateral and vertical resolution: AFM

- Single or few traces for bow, roughness, shape: stylus
Mature Technologies Offer a Variety of Specialized Configurations

Increasing Functionality and Automation

GT-K0

GT-K1

GT-X3

GT-X8

NPFlex

SP9900
Accuracy, Precision, and Resolution Are All Necessary For Good Metrology

- Precision is the repeatability of a measurement result
- Accuracy is closeness of the average result to a true value
- Both are essential for proper metrology
- Precision relates to resolution, but is not the same

High precision, low accuracy

High accuracy, low precision
Resolution Specifications Are Often Confusing

- Mathematical resolution is often used instead of something relating to a measurement
  - Some systems claim <1pm resolution. The helium (smallest) atom is 31pm in diameter!
  - 20 significant digits might not be meaningful, nor might 16 camera bits
- Lateral resolution often confused with pixel (or sample) spacing
  - For contact systems, the resolution is different along the scan direction as compared to between scan lines
  - For microscopes, optics often determine the resolvable feature size
  - Even when not optics limited you need at least 2 (preferably 3 or 4) pixels across a feature to resolve it
Many Factors Affect Resolution

- **Measurement Setup**
  - Scan speed – trade resolution for throughput
  - Tip size (stylus) or wavelength/optics (optical)
  - Field of view (optical)
  - Processing algorithm – analyze differently based on the measurement needs
  - Systematic errors that can mask real features
- **Sample properties**
  - Amount of dynamic range of the instrument being used
  - Signal to noise varies based on roughness, slopes, feature spacing
- **Environment**
  - Temperature drift during a measurement
  - Acoustic Noise
    - Can move the part during measurement
    - Can affect the instrument itself
  - Floor vibration
Data Point Density Sometimes Affects Resolution, But Might Not

- Optical systems often limited by the camera at low resolutions
- At high magnifications (>20X) most all optical systems are limited by the optics
- Stylus systems typically limited by the tip size, but can be limited by sampling rate in X or Y directions
- Even AFM’s must account for the tip on fine geometries
Submicron lateral resolution: 50nm stylus

50nm stylus can successfully access base of 270nm deep trench
Lateral Resolution of Microscopes Are Determined by the Optics and the Camera

System is called:

- **“detector limited”** if $\varepsilon \gg 0.6 \frac{\lambda}{\text{NA}}$
- **“optics limited”** if $\varepsilon \ll 0.6 \frac{\lambda}{\text{NA}}$

Effective lateral spatial sampling = $\varepsilon = \Delta / M$

where $\Delta$ = pixel spacing & $M$ = magnification
Optics Must Provide the Required Detail and Sampling

Monocrystalline Solar Cell
Sample Size Can Affect If Your Results Are Meaningful

- Surface finish correlates to solar cell efficiency only when examining large enough areas
- The necessary sampling depends on your process and metrology goals
Sample Size Can Affect Resolution: Confocal gives High Noise at Lower Magnifications

- Plots below show the signal used to determine the surface for a line of pixels as you go through focus.
- Signal changes drastically with the magnification.

Only a few objectives usable for measurement

Ra=472nm  Ra=74nm  Ra=12nm  Ra=7nm  Ra=4nm
Interferometric 3D Microscopes Are Unaffected by Magnification

- Plots below show the signal used to determine the surface for a line of pixels as you go through focus.
- Signal is unchanged no matter the magnification.

Any objective can be used for measurement.

Ra=4 nm  Ra=4 nm  Ra=4 nm  Ra=4 nm  Ra=4 nm  Ra=4 nm  Ra=4 nm  Ra=4 nm
Knowing Your Resolution Target Can Be Difficult

- What size defects or deviations matter?
- What parameters are important?
  - Roughness
  - Does Ra mean the same thing to you and your customer (or vendor)?
  - Heights
  - Curvature
  - Width
  - Defect Count
  - Structure size
- What tolerance is acceptable on those parameters
  - Each parameter will be resolved differently even with the same measurements!
- What areal coverage is needed for statistical significance?
Resolution Guidelines

• Roughness
  • For polished surfaces, use the highest lateral resolution that meets your throughput needs
  • For rougher surfaces, make sure you capture the dominant frequencies
  • Use the highest vertical resolution that meets your throughput needs
  • Make sure you filter the data appropriately so you are measuring roughness!

• Defects
  • Use modeling or failure analysis where possible to determine critical defect sizes
  • Covering more area may be more important than seeing fine features
Optimizing Resolution is a Balancing Game

- Many Tradeoffs
  - Setup complexity
    - Reference subtraction
    - Alignments
    - Fixturing
  - Measurement time
    - Scan speed
    - Averaging
    - Sample spacing and field of view
  - Data processing choices
    - Filter selection
    - Data interpolation
  - Analysis results
    - How many calculations?
    - How is a part pass/failed?

0.5 seconds - .5nm noise floor

10 seconds - .02nm noise floor
Two ‘bad’ metrics: Magnification and Sampling

**Magnification:**
- Optics companies define as ratio of pixel size on part to pixel size on camera.
  - 100X magnification with a 10mm camera means 100nm pixel spacing
- Some companies define this as ratio of pixel size on part to screen size:
  - Comes from SEM world
  - Typically you see 20,000 to 100,000X magnification for a 100X objective
  - So if you had a movie projector, you could get 10,000,000X magnification!
- Better to use **field of view (scan length for stylus)**, since it relates to the area you measure

**Sampling:**
- How closely together you can take data
- Some companies with 30 µm spot size or 20 µm stylus tips talk about 100nm sampling – this doesn’t help you see anything
- Sometimes sampling relates to lateral resolution, but often does not
  - A 50X objective may have 100 nm sampling, but only resolves 350nm features
- Use **lateral resolution or measurable feature size** instead, and ensure that it’s measured against what feature sizes can be seen
System Accuracy Will Be Affected By Your Calibration Standards

- Step uncertainty is quite large at 0.5 to 2.5%
  - Creates ‘empty’ performance as it is several orders of magnitude worse than repeatability of the system
  - Better calibrated steps are quite expensive: >$10K each
  - Example: Step repeatability is 0.05% but your calibration standard is 1% accurate. Your result could just be very consistently wrong...how do you use the data? Why bother with such good repeatability?
- Below are values from a typical step standard vendor.

<table>
<thead>
<tr>
<th>Nominal Step Value (µm)</th>
<th>Typical Uncertainty (µm)</th>
<th>Typical Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>+/- 0.0021</td>
<td>+/- 2.2</td>
</tr>
<tr>
<td>2</td>
<td>+/- 0.018</td>
<td>+/- 0.95</td>
</tr>
<tr>
<td>10</td>
<td>+/- 0.070</td>
<td>+/- 0.7</td>
</tr>
<tr>
<td>25</td>
<td>+/- 0.151</td>
<td>+/- 0.6</td>
</tr>
<tr>
<td>50</td>
<td>+/- 0.266</td>
<td>+/- 0.55</td>
</tr>
</tbody>
</table>
Some Systems Can Self Calibrate

- Separate signal continuously monitors the measurement.
- This is known as a second-level traceable, internal standard...close to an “absolute” standard.
- Each scan is monitored continuously over the entire scan range.
- Uncertainty can be significantly reduced.
- Stability improves as well as environmental factors are continuously accounted for.
Comparing Results Between Systems Has Many Pitfalls

- “New System X measures a part 10nm differently than our old system. How do we offset System X”
- “I measured some parts across the two systems and the correlation is terrible!”
  - How was each system calibrated?
  - How do results vary within and across systems of each type?
  - Can the two systems detect the same features?
  - Are you examining the same areas on each system?
  - Do the analysis algorithms on the two systems match?
  - Is there sufficient range in the values for correlation to be meaningful?
Standard Error is Used to Evaluate Agreement Between Two Systems

- Good for parts with small range in values compared to the average
- Assumes measurement of the same features
- Two methods are considered agreeable to twice the calculated standard error
- Avoids having to know the true sample standard deviation required by the correlation coefficient

**Correlation coefficient**

\[
R = \frac{\sigma_T^2}{\sqrt{\left(\sigma_{sys1}^2 + \sigma_T^2\right)\left(\sigma_{sys2}^2 + \sigma_T^2\right)}}
\]

**Standard error: standard deviation of the difference**

\[
\sigma_{SE}^2 = \sigma_{sys1}^2 + \sigma_{sys2}^2
\]
Visual Comparisons Might Be Enough to Give Confidence in Results
Numerical Correlation Might Vary Depending on the Parameter

Dektek and Optical Data for Key S Parameters

Offsets are due to differing lateral resolutions
Good correlation means consistent process control is possible

Linear Regression Graphs

90% Correlation! 86% Correlation! 99% correlation!
Roughness Standards Can Also Demonstrate 3D Microscopy Correlation to Contact Profilometry

![Graph showing Veeco WLI Vs Contact Stylus - PEEK](image-url)

- **Medical Grade Polished**
- **Injected Molded**
- **Lightly Stoned**
- **Stoned then Bead Blasted**
- **Polished finish**
- **600 Grit Paper finish**
- **600 Grit Stone finish**
- **Worn Top Hip Virgin**
- **Worn Middle Hip Joint Virgin**
- **Worn Bottom Hip Joint Virgin**
- **Worn Top Hip Carbon**
- **Worn Middle Hip Joint Carbon**
- **Worn Bottom Hip Joint Carbon**

**Axes:**
- **X-axis:** Various surface finishes
- **Y-axis:** Roughness in nm

**Legend:**
- **NP Flex**
- **Dektak**
The Most Important Thing for Choosing a Measurement System: Measure YOUR Sample YOURSELF

- Don’t rely on a scripted demonstration to make any determinations
- Perform the measurement yourself
  - Intuitive?
  - Simple setup?
- Measure time to data
- Change some variables, see what happens
Understand The System Performance For Your Needs

- Compare sequential measurements
  - Subtract results and examine the stability
  - Quick test of ‘true’ resolution

- How do results vary over time?
  - Over the course of a day
  - Overnight
  - Weekly

- Do you have the standards you need to control the metrology?
  - Sometimes a step or flat is fine
  - Might need a ‘golden’ part

10µm Step with Continuous Calibration
StdDev=5.9nm

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Averaging Can Reduce Noise and Improve Vertical Resolution

- Random (most) noise reduces by the square root of the number of averages.
- Averaging can help see finer detail than is otherwise possible.
- Examining Difference Measurements can tell you the noise floor you are achieving.
- Averaging may not help in loud or high vibration environments.

![Graph showing Ra vs. # of averages](image)

Ra of Difference Measurement vs. # of averages

- # of Averages
- Ra (nm)
- 0
- 0.05
- 0.1
- 0.15
- 0.2
- 0.25
- 0.3
Systematic Errors Exist on All Systems

- Scan stage flatness affects stylus results
- Optical aberrations affect microscopes
- Measure ‘perfect’ or known parts and look at the commonality between measurements
- Errors are typically near-constant and can be subtracted to improve resolution
- Details may then be observed which were previously impossible
ISO Compliance of Analyses Should Be Verified Where Necessary

- Vendors should have verified using NIST, NPL, or other recognized standards bodies
- Dozens of 2D and 3D primary parameters are associated with standards
System Throughput or Time to Data
Should be Understood

- Part preparation
- Part load and mounting
- Finding the measurement area
  - Automated vs. manual
  - Tolerant of errors?
- Setting up the measurement
- Measurement time
- Analysis time
- Report generation/databasing

- Often ‘measurement time’ is <1/3 overall time to data
- Be wary of ‘scan speed’
You Control Many Factors That Affect System Performance

• System placement
  • Near air vents?
  • Near sources of vibration?
  • Stable temperature?

• Part Fixturing
  • One of the most important elements for reliable results
  • Vacuum? Clamping?
  • Does the fixture deform the part?
  • Do you need pattern recognition due to placement variation?

• System setup
  • Simple optimization can improve throughput and stability
  • Proper analyses
  • Advanced training will save time and money
  • Production mode can limit operator choices
The ‘Right’ System May Be More Than One System!

- AFM: Highest lateral resolution with multiple modes and applications
- 3D Microscopes: Highest Z resolution, non-contact high-speed 3D measurements
- Stylus: High Z with excellent measurement repeatability

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Choosing a Measurement System Is Not Simple

- Does the system have the required performance on your parts, with your people, in your environment

- Is additional capability (automation, self-calibration, mechanical stability) worth the investment?
  - How critical are the results?
  - How quickly do you need feedback?
  - How will a given increase in yield help your business?

- Are you getting the solution you need?
  - Is it flexible enough for the long term
  - Do you have access to the required expertise
  - Will the provider be there for you
Thank You!
Questions?

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