An introduction to non-contact surface metrology
Dr. Joanna Schmit

Atomic Force Microscopy
3D Optical Microscopy
Tribology
Automated AFM
Stylus Profilometry
Mechanical Testing, Nano Indentation

Innovation with Integrity
WHAT WE WILL COVER

» Why 3D non-contact metrology and why with interferometry

» Theory of interferometry – how fringes are created in monochromatic and white light illumination

» Easy fringe interpretation

» Ideal measurement modes for your surface type

  PSI – monochromatic illumination

  VSI – white light illumination
Surface metrology plays an important role in the functioning of machined, etched, molded parts in different market areas like:

- automotive/aerospace
  - bearing surfaces
  - shafts
  - dynamic seals
- high-brightness LED
- solar
- semiconductor
- medical device markets

“If you can’t measure it, you can’t make it”
Bruker 3D microscope technology
White Light Interferometry

• WLI 3D microscope provides
  • non-contact
  • fast
  • accurate
  • repeatable
  • areal topography including shape, waviness and roughness

• Easy measurement
  • Focus and go!
What are these fringes?

Why are they useful in surface metrology?
Why contour map is useful?

• The contour lines that are very close together indicate an extremely steep slope.

• Values buy the contour lines tell us that surface rises from about 4500 feet to 5100 feet.

• A perfect bulls-eye shape indicates a circular mountain.

• The open center circle inside the 5100 contour line indicates that the top of the mountain is a flat plateau.

http://www.compassdude.com/contour-quiz.shtml
Now take a test and see if you “feel” the fringes

Match the measurement result with the fringes
Interferometry, Interferometer

**Interferometer** is an optical device that divides a beam of light exiting a single source (like a laser or LED) into two beams and then recombines them to create an interference pattern. The combined pattern can be analyzed to determine the difference in paths the two beams traveled.
• **Wave front** - surface connecting all points that light traveled the same optical length from the source.
Typical Interferometer

- The expanded beam exiting from the light source is divided by a Beamsplitter into two beams.
  - One beam is reflected from the Reference Mirror, and the other one from the Sample.
  - These two beams are recombined by the Beamsplitter to interfere.
- The imaging lens images the interferogram onto the CCD camera.

Optical Path Difference (OPD)
- difference in optical path lengths that beams travel in Reference and Test arms.
Tilt of one of mirrors in interferometer

If one of the mirrors is slightly tilted, then the reflected beam (wavefront) also is tilted. If mirror and flat sample are perfectly perpendicular, then reflected wavefronts are parallel.

For two tilted and flat wavefronts, an interferogram of straight, parallel, light and dark bands will be formed.
Interferogram for flat wavefronts with tilt and monochromatic light source

Multiple $\lambda$ distances between wavefronts, where $\lambda$ is the wavelength of the source.

Interference between two wavefronts is **constructive** at these multiple $\lambda$ points, **destructive** at others, forming an interferogram.

Fringe spacing corresponds to $\lambda$ path difference between wavefronts.

Intensities are as follows:
- $\lambda$
- $2\lambda$
- $3\lambda$
- $4\lambda$

**Tested beam** (wavefront)

**Reference beam** (wavefront)

**Two interfering wavefronts**

**Intensity profile of interferogram.**
Change in tilt causes change in # of fringes

**NULL FRINGES**

When wavefronts are parallel then the fringes are nulled and almost uniform intensity is visible in the field of view.

The number and spacing of fringes changes with tilt.
Change in length of one of the arms introduces a phase shift between interfering wavefronts causing fringes to shift to a new location.

Note that number of fringes and their orientation remains the same.
Fringe demo
Wavefront reflected of the surface
When one wavefront is spherical and the other is flat, and in addition there is some tilt between interfering wavefronts, then the fringes will be curved. When tilt is not present, the fringes are circular.
White light fringes

Interferogram can be obtained with a white light source, such as LED

- Beams at different wavelengths interfere
- Sets of fringes for different wavelengths are created
- Spacing between fringes depends on wavelength

Fringes for:
- blue light
- green light
- yellow light
- red light
• The sum of all interference signals is observed forming a fringe pattern with quickly decreasing modulation.
• Fringe modulation achieves a maximum for equal optical paths of both beams (there OPD=0).
Interference Microscope

Interference microscope combines an interferometer and microscope into one instrument.

It is used for measuring engineering surfaces that demand testing with high resolving power.
Interference Microscope Diagram

- Detector Array
- Digitized Intensity Data
- Beamsplitter
- Translator
- Microscope Objective
- LED Source
- Aperture Stop
- Field Stop
- Mirau Interferometer
- Sample
Michelson Interferometer

2X, 5X
small divergence of beam
long working distance
area:
5mm x 5mm – 1mm x 1mm

Sample

Beamsplitter Cube

Reference Mirror

Microscope Objective
Mirau Interferometer

10X, 20X, 50X, 100X
medium divergence of beam
medium working distance
Area
1mm x 1mm – 60um x 60um
Mirau Interferometer

Microscope Objective

Reference

Beamsplitter Plate

Sample
Linnik Interferometer
Tilt between wavefronts introduced via tilt of the objective
Interference objectives

- **Michelson (1.5X-5X)**
  - Low magnification
  - Large field-of-view

- **Mirau (10X-100X)**
  - Medium to high magnification
  - Medium to small field-of-view

- **Linnik (any magnification)**
Principles of Interferometry

- Difference in optical paths will cause a difference in phase

- Interference will be constructive at some points, destructive at others, forming an interferogram.
MONOCHROMATIC ILLUMINATION
PHASE SHIFTING INTERFEROMETRY

PSI
Two-beam interference fringes

\[ I = I_{\text{background}} + 2I_{\text{amplitude}} \cos(\phi + \phi'(t)) \]

When we change \( \phi'(t) \) in constant fashion over the full field the fringes will shift.
Four Step Method

\[ I(x,y) = I_{\text{background}} + I_{\text{amplitude}} \cos[\phi(x,y) + \phi'(t)] \]

<table>
<thead>
<tr>
<th>( I_1(x,y) = I_{\text{background}} + I_{\text{amplitude}} \cos [\phi (x,y)] )</th>
<th>( \phi' (t)=0 )</th>
<th>(0°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_2(x,y) = I_{\text{background}} - I_{\text{amplitude}} \sin [\phi (x,y)] )</td>
<td>( =\pi/2 )</td>
<td>(90°)</td>
</tr>
<tr>
<td>( I_3(x,y) = I_{\text{background}} - I_{\text{amplitude}} \cos [\phi (x,y)] )</td>
<td>( =\pi )</td>
<td>(180°)</td>
</tr>
<tr>
<td>( I_4(x,y) = I_{\text{background}} + I_{\text{amplitude}} \sin [\phi (x,y)] )</td>
<td>( =3\pi/2 )</td>
<td>(270°)</td>
</tr>
</tbody>
</table>

\[ \tan[\phi(x,y)] = \frac{I_4 - I_2}{I_1 - I_3} = \frac{I_b + I_a \sin \phi - I_b + I_a \sin \phi}{I_b + I_a \cos \phi - I_b + I_a \cos \phi} = \frac{\sin \phi}{\cos \phi} \]
Computerized interferogram analysis

**Phase Shifting Interferometry (PSI)**

- Used for testing smooth objects with very high precision
- Vertical resolution 0.1 nm
- Typically monochromatic light used to illuminate sample.

\[ \tan(\phi) = \frac{I_4 - I_2}{I_1 - I_3} \]
Testing Flat Surfaces

- Is the reference mirror really flat?

  Fringes
  - visually seem to be perfectly straight

  Phase map
  - reveals that interfering wavefronts are not perfectly flat. Here the peak-to-valley (Rt) is on order of a few nm.
Principles of PSI Operation

- The fringes are shifted by fringe/4
- Resultant arrays of intensity solved for Phase.
- Phase is converted to surface height.
Can my sample be measured with PSI mode?

- Is my sample smooth? Is the rms less than 30nm?
  - Visual assessment – Is my sample shiny?

- Does my sample have steps? Are they less than 140nm?

No problem measuring even 1nm steps
WHITE LIGHT ILLUMINATION
VERTICAL SCANNING
INTERFEROMETRY

VSI
(WLI)
Operation of 3D WLI microscope

White Light illumination
For rough, tall and discontinuous surfaces
Vertical resolution 1-5 nm for each objective
Sample always measured at the best focus
Fringes are like a focus sensor
Max height 10mm
Scanner speed 5 to 80 um/sec
• Noise floor – 3 nm for every objective 1.5X-115x!!!

• Max heights - 10mm
• Slope – 60deg +
• Low reflectance <0.5%
Typical white light fringes for rough surface

Focus Position A

Focus Position A
Principles of vertical scanning interferometry

- Fringes are localized around the best focus

- Measure the intensity at each pixel as the objective is moving vertically.

- Algorithm finds position of fringes to determine the height of the surface at each pixel.

- Measure changes in surface height up to 10mm (depends on working distance of given objective).
Advantages of VSI

- True 3D measurement of surface area.
- Ability to measure non-specular, rough surfaces.
- Good results with low contrast fringes.
- Results independent of intensity variations across field of view.
- Vertical height limited only by scanner and objective working distance.
- No step height ambiguities.
- Tested area always in focus.
Which fringes can be analyzed with PSI and which with VSI?
3D Microscopy – Versatile
Rough and Smooth Samples

White Light Interferometry – WLI

- Vertical resolution ~3 nm
- Steps or surface variations up to 10 mm
- Surfaces with rough/steep surfaces
- Speed 5-80um/sec

Phase Shifting Interferometry – PSI

- Vertical resolution <0.1 nm
- Smoothly varying surfaces
- Polished materials, small height differences
- ~1 sec
High resolution VSI
Skin

Bumped printed circuit board.

Cotton cloth, 1mm x 1mm.

Gravure Roll

Hard disk suspension arm.

3D WLI microscope

Compact disk data pits 11µm x 13µm.

Grasshopper Eye 230um x 300um.
WLI 3D microscopes...

- ...are fast, non-contact, easy to set up
- ...have excellent SNR, resolution and accuracy
- ...measure surface topography and roughness of variety of samples:
  - 60° + slopes
  - <0.05% reflectance
- ...can image with color CCD*
Thank you!!!

productinfo@bruker-nano.com

+1 520 741 1044 x 1018
Joanna.schmit@bruker-nano.com

Joanna Schmit, Ph.D.
Senior Staff Optical Engineer
Bruker NSD, SOM

www.bruker.com

For more information on fringe analysis go to:
Optical Shop Testing
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THANK YOU!!!
Apply Benefits to Industry Problems

Semiconductor Applications example

- Broad range of applications including
  - Laser probe mark depth
  - Sensor dimensions and frequency performance (MEMS, DMEMS)
  - Cu wire bonding (bond force optimization, near line inspection)
  - Multichip Module HDI production inspection