

Application Note #503

Comparing 3D Optical Microscopy Techniques for Metrology Applications

3D optical microscopy is a mainstay metrology technology across a wide range of industries. There are a few techniques that provide a 3D surface representation from a microscope image, including the two key techniques of white light interferometry (WLI) and confocal microscopy (LSCM). These two methods are ubiquitous for measuring nanometers-to-millimeters surface heights. The principle of operation for each method provides different advantages and disadvantages, and this application note discusses the distinct metrology advantages of Bruker's ContourGT® 3D optical microscopes over confocal microscopes for certain applications. Key to these advantages is the ability to maintain subnanometer vertical resolution and 0.1 nanometer RMS repeatability, regardless of magnification or field of view.

Principles of Measurement

Confocal microscopy was originally developed for imaging of biological cell and tissue samples, and had very little to do with metrology. This method's main strength continues to reside in the imaging area as opposed to critical industrial metrology applications. In confocal microscopy, the sample is advanced vertically in steps such that each point on the surface passes through focus. A very small aperture is placed in front of the detector to admit light from a single

point as it passes through focus. In LSCM, only one point is measured at a time, requiring raster scanning in the X and Y directions as well as in the Z axis to obtain data for each point on the surface. A limitation of this approach is that it becomes very time-consuming to capture data over a large field of view. With 3D microscopy based on WLI, a vertical scan along the Z axis is made so that each point of the test surface passes through focus and the X and Y data are captured with a single acquisition at each Z axis step. This provides a speed advantage over confocal methods where each point needs to be scanned in both X-Y and Z (see figure 1). It should be noted that some types confocal microscopes utilizing alternative technologies (e.g., spinning disk multiple pinhole types) can image multiple points simultaneously, but all 3D microscopes based on WLI capture X-Y and Z data simultaneously.

WLI-based 3D optical microscopy was, on the other hand, developed from the very beginning for industrial metrology applications. In a 3D optical microscope based on WLI, light approaching the sample is split and directed partly at the sample and partly at a high-quality reference surface. The light reflected from these two surfaces is then recombined. Where the sample is near focus, the light interacts to form a pattern of bright and dark lines that track the surface shape. The specialized microscope objective is scanned vertically with respect to the surface so that each point of

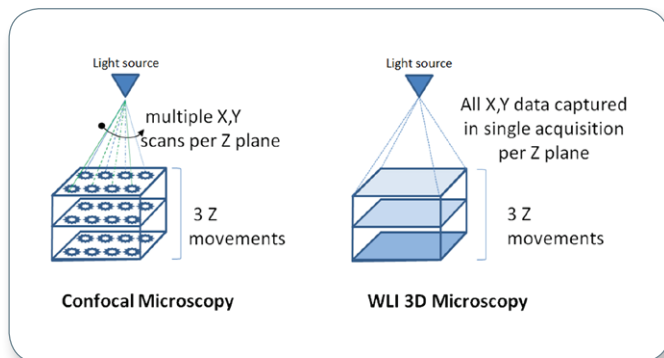


Figure 1. Diagram outlining different scanning methods used by confocal microscopes and 3D microscopes.

the test surface passes through focus. The location of the maximum contrast in the bright and dark lines indicates the best focus position for each pixel, and a full 3D surface map of the surface within the field of view of the microscope is generated. Onboard software is then employed to analyze these data to calculate different parameters of interest, such as surface texture, roughness or other critical geometric dimensional information.

Vertical Resolution

Vertical resolution is usually the most basic performance characteristic in the surface profile measurement application. By the nature of their operation, confocal systems must continuously move the stage around to raster scan the surface so vertical resolution in confocal microscopy is limited by the axial point spread function. The height of each pixel location is found by detecting the peak intensity or by calculating the center of mass of the intensity distribution around the focus position. The intensity envelope is narrow for high-magnification objects, but at lower magnifications the intensity envelope becomes wider as the objective's numerical aperture (NA) and depth of field increase. As shown in figure 2, roughness and height data for confocal microscopes with 5x and 10x objectives are almost unusable, and even 20x objectives do not provide very accurate data. Acceptable vertical resolution is only achieved with an objective 50x magnification or above, which limits the field of view. Data stitching is then required to map larger areas, significantly increasing measurement time.

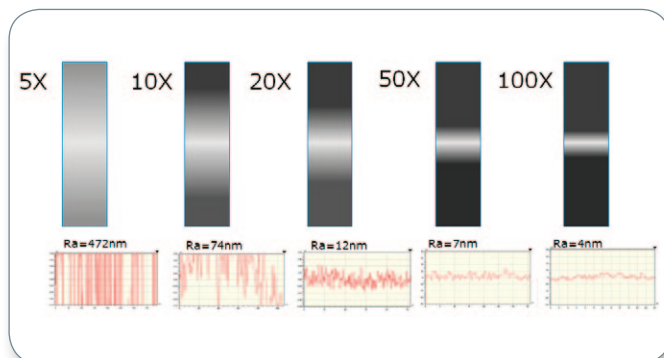


Figure 2. Confocal microscopes produce a wider, weaker signal for lower magnification objectives.

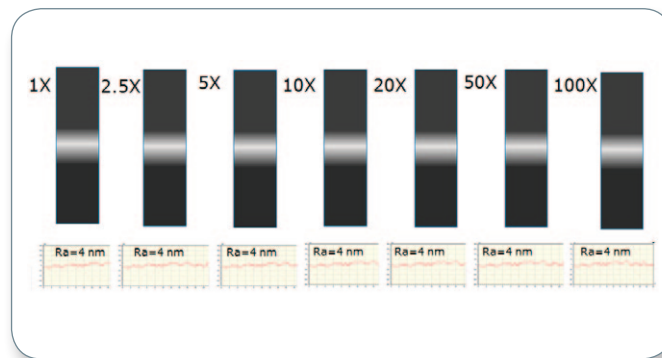


Figure 3. WLI microscopes provide a constant, narrow signal for all objectives.

In 3D microscopy based on WLI, the fringe envelope remains very narrow at all magnifications (see figure 3). This feature, combined with fringe phase detection, enables sub-nanometer vertical resolution. This differential advantage allows use of lower magnification objectives for true metrology applications while maintaining equivalent or better vertical resolution. The lower magnification objectives provide much greater fields of view thus enabling much higher throughput combined with highest Z accuracy measurements. Current WLI-based microscopes, such as Bruker's ContourGT, are ideally suited for detailed surface profile analysis with low-magnification lenses. These microscopes can be used to measure the surface profile at any magnification with some simple consideration for the spatial scales that are important for the analysis. Rapid stitching can also be used for areas larger than 5x5 millimeters (see figure 4). This stitching capability, combined with the larger field of view provided by WLI-based 3D microscope objectives, provides a very powerful speed and throughput advantage.

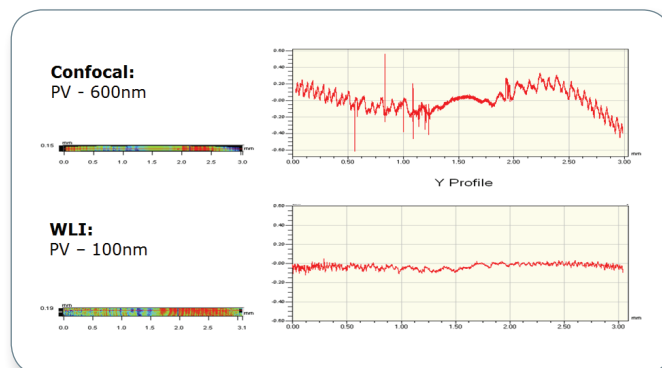


Figure 4. Comparison of a stitched measurement covering 3mm taken from a 13mm radius sphere (shape and form removed) measured with a confocal and a WLI 3D microscope using a 50x objective. The 3D microscope based on WLI provided better stitching and smaller aberrations, indicated by the 100nm Peak to Valley (PV) residual, a factor of six improved over the confocal based 3D image.

Lateral Resolution

There are two possible limits to the lateral resolution of an optical system. The first is pixel-limited resolution, where two adjacent features are imaged into a single camera pixel and thus there is no way to distinguish between the features in the final digitized image. Another possible limitation to lateral resolution is diffraction, where there are at least two camera pixels for each feature, but multiple features are blurred by the optics and cannot be readily distinguished from each other. For visible light 3D microscope systems, this spatial resolution limit is usually about 350 to 400 nanometers. High-magnification objectives, such as 20x, 50x and 115x, typically produce diffraction-limited images.

Bruker's exclusive AcuityXR™ enhancement for ContourGT 3D optical microscopes uses an algorithm to reconstruct the object that has been imaged by an optical system free of diffraction. Through multiple scans and system modeling, AcuityXR produces a measurement with twice the number of pixels in both the X and Y directions than is possible with a standard interferometric measurement. AcuityXR utilizes a patent-pending iterative technique with feedback from the metrology hardware to systematically reduce system noise and mitigate blurring effects caused by diffraction on the final calculated surface height. Features at 130 to 500 nanometers on smooth or stepped surfaces can be resolved by the use of an interferometric measurement mode on a WLI 3D microscope that resolves greater surface detail without compromising the many other benefits of these systems. Figure 5 compares a measurement taken with a standard WLI 3D microscope (left) with one taken with a WLI 3D microscope plus AcuityXR enhancement (right). In the image on the right, enough resolution is gained to reveal the full separation between the lines, and fine details of the linewidth variation are visible.

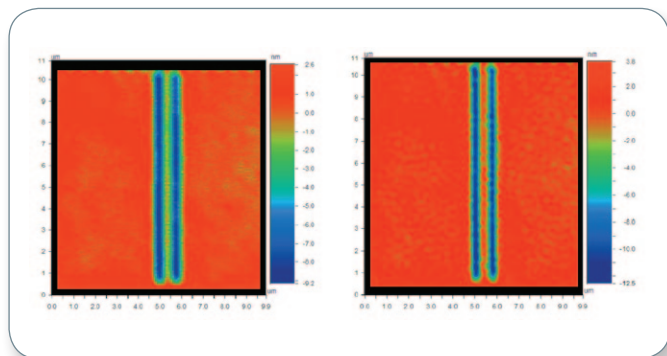


Figure 5. 350nm linewidth measurements taken with a standard 3D microscope based on WLI(left) and the same microscope with AcuityXR enhancement (right) shows how the latter provides high levels of feature differentiation.

Measurement Speed

Confocal microscopes typically achieve data acquisition speeds on the order of 0.3 megapixels per second, in units of sections, or images. In order to achieve higher speeds with a confocal microscope the field of view must be reduced (e.g., for greater than 10 microns per second, a single line profile must be taken rather than a whole image). 3D microscopes based on WLI, on the other hand, provide scan speeds up to 100 microns per second vertically, with the entire field of view imaged in a fraction of a second. To illustrate this point, Table 1 compares best resolution data estimates for equivalent inspection areas measured by LSCM and WLI-based 3D microscopes.

| 3D Microscope Basis Technology | Area of Interest (mm square) | Ra-Metal Sample (nm) | Time (seconds) |
|-----------------------------------|------------------------------|----------------------|----------------|
| LSCM-50x Objective | 0.1 | 7 | 1 |
| Stitch 50x - 100 sections | 1 | 7 | 100 |
| Stitch 50x - 2500 sections | 5 | 7 | 2500 |
| WLI - 50x Objective | 0.1 | 4 | 1 |
| 5x Objective | 1 | 4 | 1 |
| Stitch 5x - 4 sections | 5 | 4 | 5 |

Table 1. LSCM and WLI Comparison of time to data for best metrology (vertical) resolution (0.3MP/sec. image for LSCM, interline transfer image acquisition for WLI). WLI-based systems produce higher quality data in much faster timescale.

Detection of Steep Angles

When initially developed, WLI 3D optical microscopes were limited in their ability to detect steep angles. However, today's 3D optical microscopes are able to measure

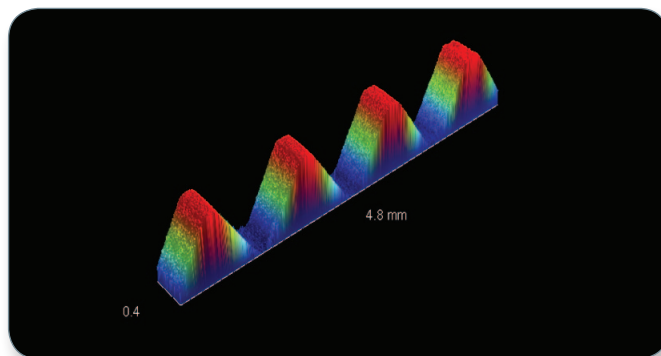


Figure 6. Lead angle of screw threads can easily be measured at 60 degrees with a WLI-based 3D optical microscope.

slopes at 60 degrees easily, as shown in figure 6, and up to 87 degrees with the latest models. When utilizing modern WLI 3D microscopes to measure very steep angles present on very smooth surfaces, such as in the patterned sapphire substrates (PSS) used to improve performance of high-brightness (HB) light emitting diodes (LEDs), data is

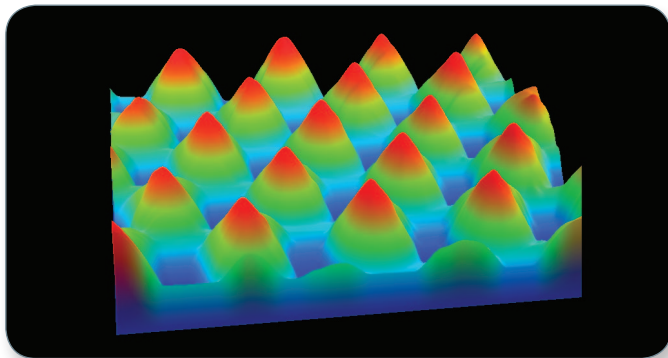


Figure 7. Patterned Sapphire Substrate image taken showing capability of WLI 3D microscopes to provide high-speed precision metrology measurements of steep angles.

mathematically calculated, and the correct height, pitch and pyramid volumes are characterized (see figure 7).

Measuring Samples over a Wide Range of Reflectances

3D optical microscopes based on WLI can be used also on samples with a wide range of reflectances. They can measure virtually anything that reflects light, from highly specular to diffuse surfaces with low or high reflectance. Additionally, 3D optical microscopes based on WLI can measure samples with reflectance as low as 0.05% and as high as nearly 100%, and can measure steep angles on a dull/diffuse reflecting surface, such as a screw thread. Samples with a combination of brightness values in the field of view, as shown in figure 8, are handled with ease. Clean data is obtained on the smooth, flat portion shown in red

even though some saturation is required in order to obtain data down into the rough machined bowl of the sample shown in blue.

WLI 3D microscopes generate data in 30 seconds or less on even steeply angled samples with no need for tilt correction. For example, the image shown in figure 9 was generated in only 30 seconds (total time to place the sample and get data).

It is true that in order to obtain the absolute best data for very smooth or very high lateral resolution requirements, it is necessary to remove sample tilt relative to the optical head. This is also true for confocal techniques.

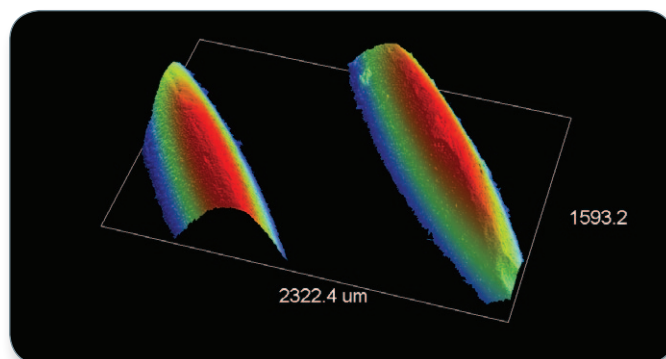


Figure 9. 5x thread image generated on a WLI 3D microscope, just by optically focusing and measuring.

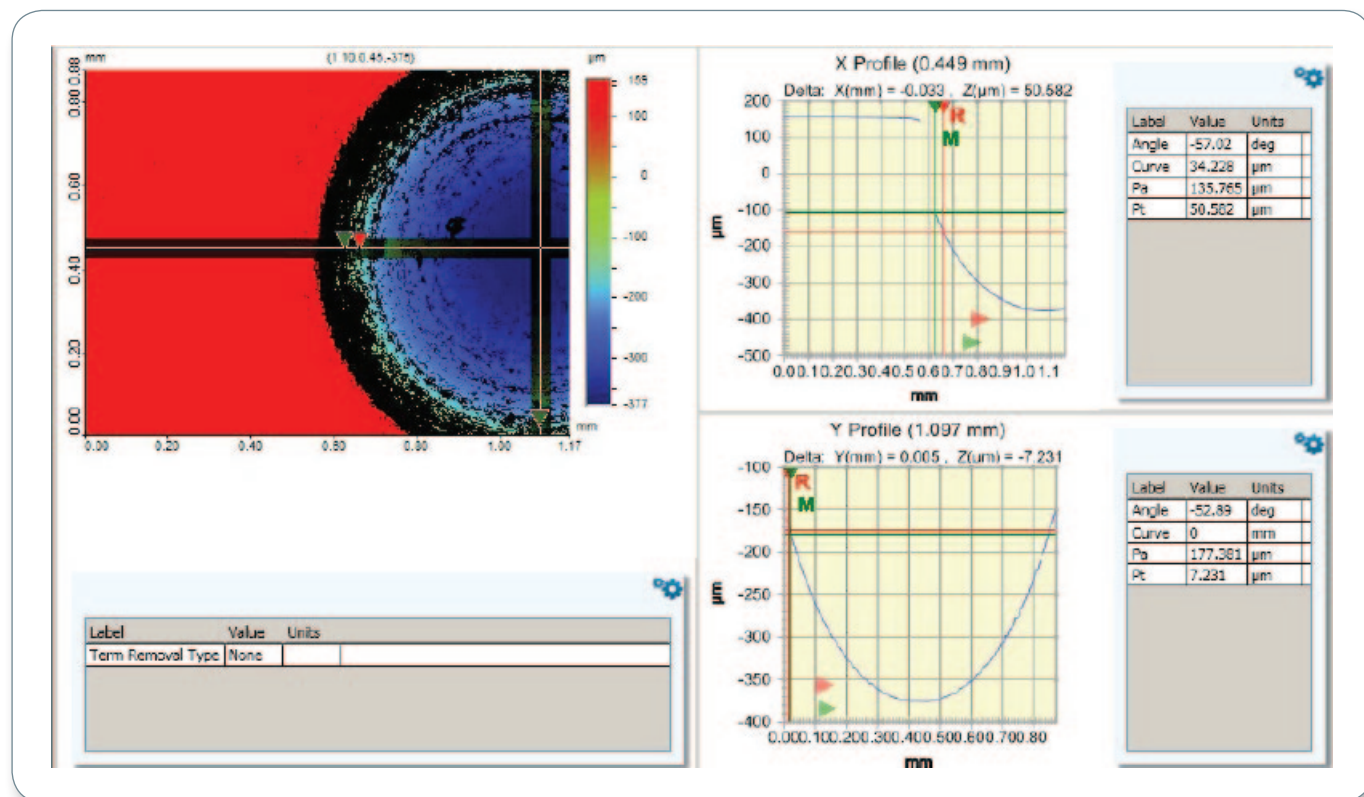


Figure 8. WLI 3D microscopes can accurately measure samples with a wide range of reflectances.

Additional Considerations

For some time, confocal microscope manufacturers enjoyed the advantage of color imaging capability, which proved useful for a small set of specific industrial applications, such as copper wire bonding (see figure 10). The latest generation of Bruker 3D microscopes based on WLI, however, offers a color imaging option that addresses these specialized applications. Now, color imaging is possible with the increased surface profile of WLI measurements and greater surface area measured at lower magnification.

Both WLI and confocal microscopes are equally sensitive to vibration and both use similar isolation mechanisms to address this concern. However, due to the greater resolution ability of WLI measurements over lower magnifications, vibration can be detected above the noise floor. For such uses, Bruker's WLI-based 3D microscope systems have been designed to take advantage of a combination of isolation solutions.

Conclusion

Measuring surface topography and the size and shape of microscopic surface features is critical in many different industries to ensure the quality of production processes. The variety of instruments used for this task, such as WLI-based 3D microscopes and confocal microscopes each have their own advantages and limitations. The latest generation of Bruker ContourGT 3D microscopes delivers a powerful combination of high-speed operation, an ability to function in factory environments, and unmatched accuracy, including sub-nanometer resolution in the vertical (Z) axis. As a result, this technology is being used in an increasingly wide range of applications, from inspecting critical wear of industrial surfaces and characterization of the tooling used to produce contact and intraocular lenses (IOLs) to measuring PSS used in HB-LEDs.



Figure 10. WLI microscopes can now produce color images, as seen here for wire bonding characterization.

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