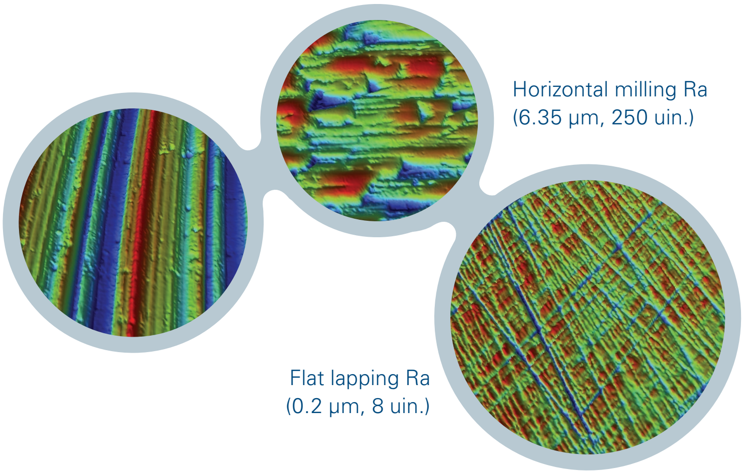


Application Note #558

Correlating Advanced 3D Optical Profiling Surface Measurements to Traceable Standards

This application note describes the advantages of the non-contact inspection method employed by 3D optical profilers, and discusses the best practices and measurement results for some specialized PTB (Physikalish-Technische Bundesanstalt) traceable roughness standards and other low-cost fingernail roughness gages. The correlation results are based on measurement factors that should be understood and considered when imaging and analyzing surface textures that range in roughness from a few nanometers to micrometers in scale. 3D optical profilers that utilize coherence scanning interferometry, also known as white light interferometry (WLI), provide fast, accurate surface measurements over large areas to quantify a variety of properties about surfaces under inspection. These profilers are being increasingly used in engineering, research, and production process control for an extremely wide range of markets, including precision machining, medical, microelectronics, MEMS, semiconductor, solar, data-storage, automotive, aerospace, and material science. Understanding how this technology correlates to traditional 2D techniques and standards, and how the increase of measurement data can be quantified and utilized are crucial to taking full advantage of the capabilities of today’s top-performing 3D optical profilers.

Advantages of 3D Optical Profiling Over Other Measurement Technologies

Surface roughness characterization started in the early 1930s with 2D stylus profilers, which were adopted as the industry standard until the development of 3D metrology instruments decades later. The many advantages of 3D optical profiler measurement systems have led the international metrology community to develop new measurement standards to take full advantage of this superior technology. Today’s most advanced surface profilers provide industry-leading speed and accuracy while maintaining the same “nanometer” Z accuracy at all magnifications. Such systems can measure a very wide range of surface parameters, including surface roughness, step heights, pitch, curvature, lateral displacement and waviness; all in a single measurement and on nearly any surface. Based on white light interferometry as seen in Figure 1, this measurement technique can quickly determine 3D surface shape over large lateral areas, up to 8 millimeters, in a single measurement. To measure even larger lateral surface areas, stitching algorithms can be applied to allow multiple lateral images to be taken and merged into one image for analysis.

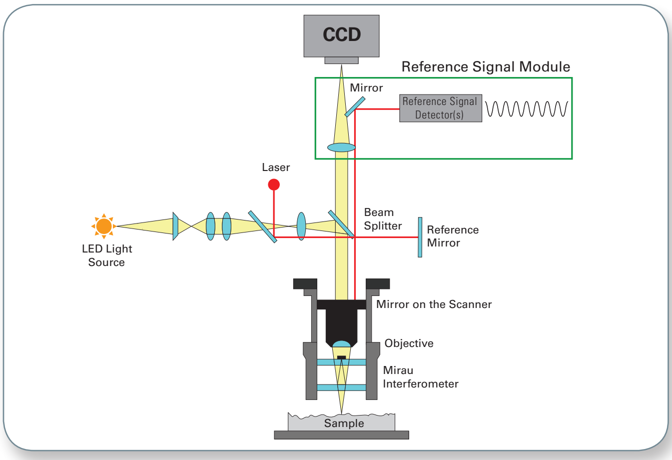


Figure 1. Basic white light interferometry schematic with Bruker's self-calibration HeNe laser.

Several other technologies either offer good resolution, fast speeds, or larger areas of measurement, but each has limitations as well. Stylus profiling, for example, offers scans up to hundreds of millimeters in length. However, each scan is only a trace along one probe-tip-wide line, which limits the area that can be analyzed without taking multiple traces. Consequently, acquisition time is relatively slow for larger areas. Similarly, confocal microscopes offer reasonable Z resolution at very high magnifications, but data acquisition time is much slower due to the scanning technology used to capture the Z height data. Lastly, optical focusing techniques are used for more coarse manufacturing surface finishes, but aren't generally able to approach the Z resolution of an interference-based 3D optical profiler, especially for surface texture on finely machined structures.

These other technologies also have other drawbacks when it comes to measuring surface topography and quantifying texture. One big drawback of contact stylus measurement is that the stylus tip needs to run perpendicular to the predominant surface pattern or surface lay of the measurement surface. If this is not the case, the tip may follow the structure of the surface and provide false surface texture results, similar to a record player needle following the grooves in a record. Another drawback to stylus measurements is the limitation in Z height measurement range. A stylus system has to use a skid plate to increase the measurement range, which allows it to measure over larger steps but then limits its ability to measure waviness or stepped features precisely, since the skid plate has to track the surface under test. This produces a sort of mechanical filtering of the surface representation. Lastly, since most stylus tips are made of a very hard material, such as diamond, to reduce tip wear and increase tip life, scans can damage the surface being measured and give false readings, as seen in Figure 2.

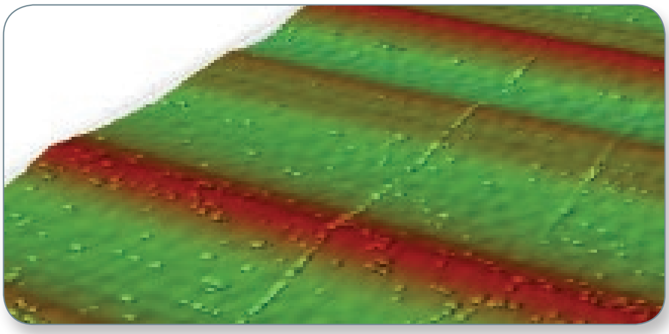


Figure 2. Stylus damage to reference standard.

Confocal microscopy finds the height at each pixel location by detecting the peak intensity or by calculating the center of mass of the intensity distribution around the focus position. The intensity envelope is very narrow for high-magnification objectives, but at lower magnifications the intensity envelope becomes wider due to the objective's lower numerical aperture (NA), which increases the depth of field. This large depth of field impairs a confocal system's ability to repeatedly find the centroid and peak intensity, and therefore deteriorates the Z accuracy and resolution. Typically, high-magnification objectives (20x and above) need to be used to gain Z accuracy, but this limits the lateral field of view. In the past, the main advantage of a confocal microscope was its ability to measure steep angles. However, with the development of higher magnification objectives for 3D optical profilers, along with the improved lateral resolution of high-resolution cameras, steep angles approaching 90° on non-mirror surfaces are now measurable by non-confocal systems.

Modern 3D optical profilers have no limitations to surface structure orientation and provide no risk of surface damage since they are based fully on a non-contact measurement technique. In addition, 3D optical profilers generally aren't Z-height limited, and have the ability to measure up to 10 millimeters in height. And, since the 3D optical profiler's fringe envelope remains very narrow at all magnifications, from 0.75x to 230x, it maintains the same high Z resolution across the field of view at any magnification.

Stylus Profiler Filtering for Traditional Measurement Standards

Many of the traditional measurement standards have been set around contact stylus results. Understanding how this technology works and the origin of the standards that came from it is necessary in any effort to correlate other technology results. A stylus contact measurement system has natural mechanical filtering due to the tip radius and taper angle of the stylus tip making contact with the surface during measurement. Typically, the taper angle is 45° to meet recommended measurement standards, such as International Organization of Standardization (ISO). The tip radius usually ranges from 1 to 10 microns. Depending on the tip model and sample roughness, the tip may not reach to the bottom of the surface profile, and also can round off the peaks and valleys, both of which will influence the surface finish results. Also it's not possible to measure surface features that are smaller than the tip itself, as shown in Figure 3A and 3B.

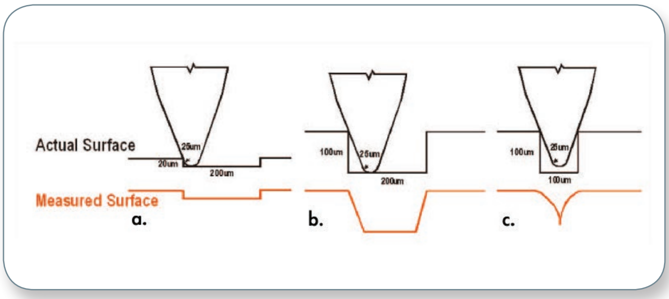


Figure 3A. This 25 μm tip easily measures larger trenches (a), but cannot accurately measure the width (b) and height (c) as the trench aspect ratio increases.

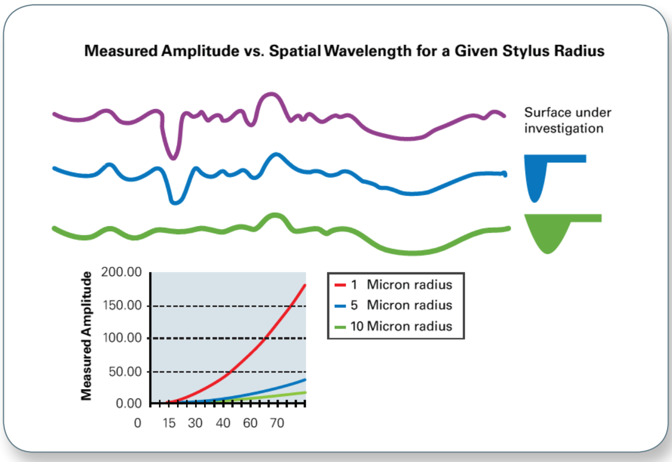


Figure 3B. Influence of tip radius with stylus measurements.

When setting up a mechanical stylus measurement, a known scan length needs to be determined. This scan length is the length of the path that the stylus traces and is called the measurement or traversing length. The spatial wavelength of the lowest spatial frequency filter that will be used to analyze the data is usually defined as the sampling length. Most industry-recommended practices or standards recommend that the measurement length should be at least seven times longer than the sampling length or the wavelength of the feature of interest. Commonly, one sample length is discarded from each end of the measurement length, as seen in Figure 4.

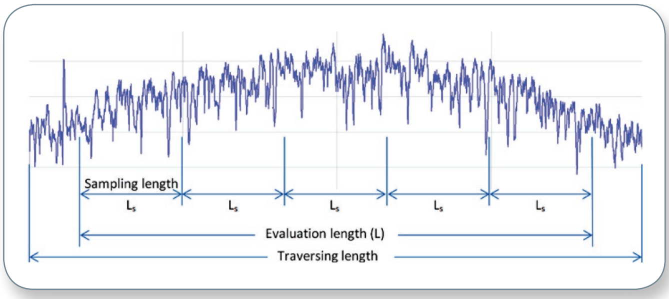


Figure 4. Total profile with divisions into sample, evaluation, and traversing lengths.

The scan that is captured is called the total profile and gets electronically leveled, usually by fitting a line thru all the data. The next step when analyzing stylus data is to apply electronic filters and cutoff filters. Typically the first step of analysis is to apply a low pass spatial frequency filter to the raw total profile to remove very high spatial frequency data since it can often be attributed to vibration, debris on the surface, or stylus deformation. Next, the data can be separated into roughness, waviness, and form by use of various other filters. A high-pass spatial filter is typically applied to obtain the roughness parameter by removing the overall form or waviness. A band-pass filter is typically applied to obtain the waviness profile. There are many other types of filters but this is the standard approach when performing contact stylus surface finish measurements and analyses, as seen in Figure 5.

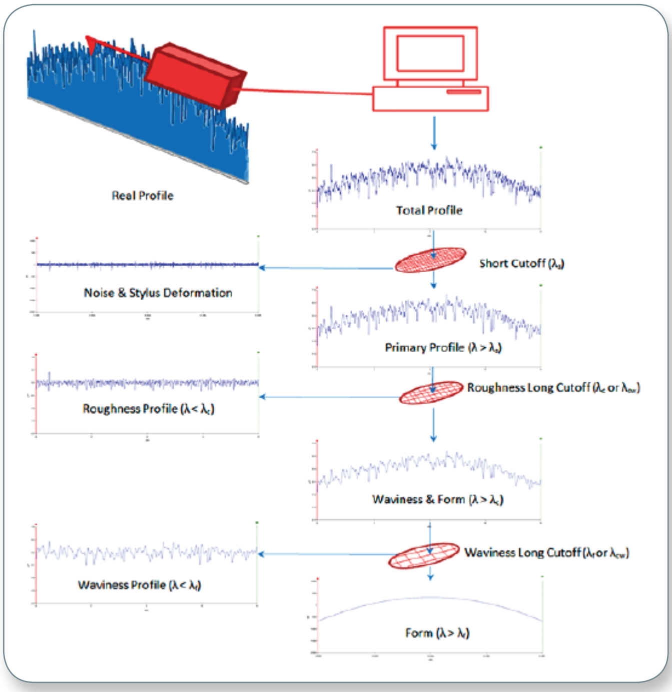


Figure 5. Electronics filters are applied to obtain roughness or form.

Most common types of manufacturing processes have a similar surface finish result, as illustrated in Figure 6A and 6B. Recommended practices from ISO and ANSI/ASME, among others, suggest sample lengths, cutoffs, and filters for those stylus measurements. When trying to correlate a non-contact measurement to a stylus measurement system, the user needs to know exactly how the stylus system was configured mechanically and electronically when capturing the data to provide the best reproducibility and correlation.

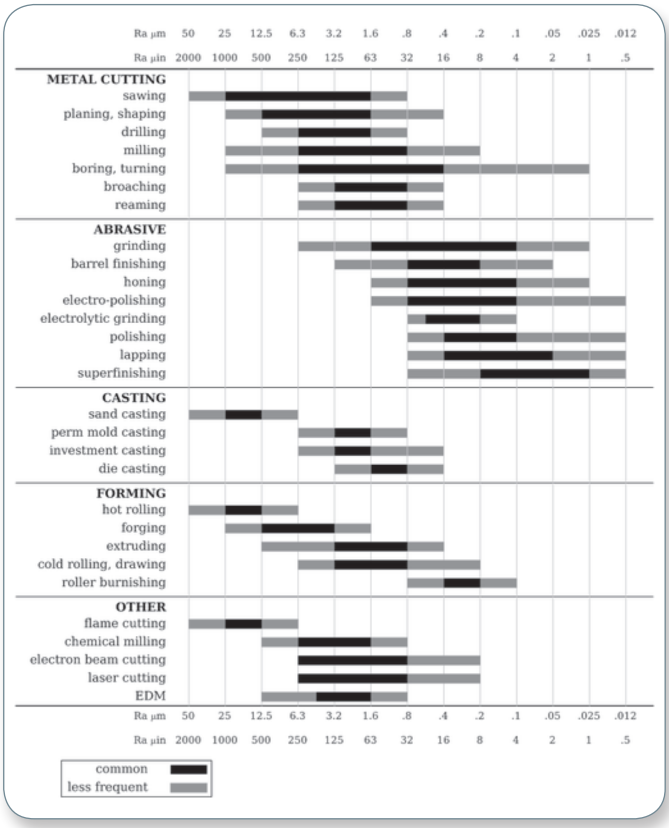


Figure 6A. Surface finish tolerances in manufacturing.

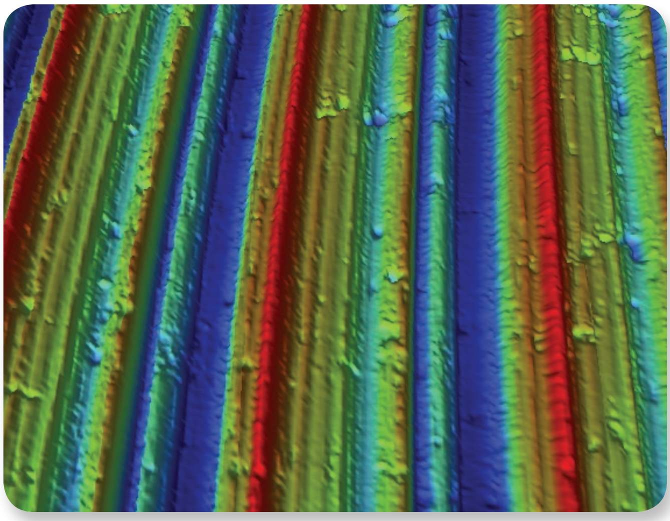
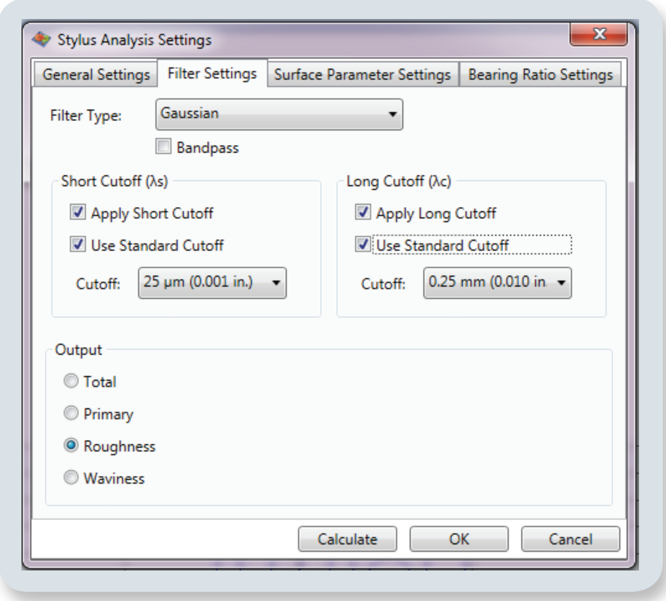


Figure 6B. Vertical milled surface measured on a 3D optical profiler.

For example, on Bruker's 3D optical profilers, their Vision64® software can be configured to duplicate a 2D stylus measurement by applying those same cutoffs and filters, as seen in Figure 7. With the advances in optical profiling over the last decade, 3D optical profilers can now accurately perform the 2D parameter measurements traditionally performed by stylus profilers, with considerable advantages in both speed of measurement and sample integrity.



Filter Type: Gaussian

☐ Bandpass

Short Cutoff (λs)

☑ Apply Short Cutoff

☑ Use Standard Cutoff

Cutoff: 25 µm (0.001 in.)

Long Cutoff (λc)

☑ Apply Long Cutoff

☑ Use Standard Cutoff

Cutoff: 0.25 mm (0.010 in

Output

○ Total

○ Primary

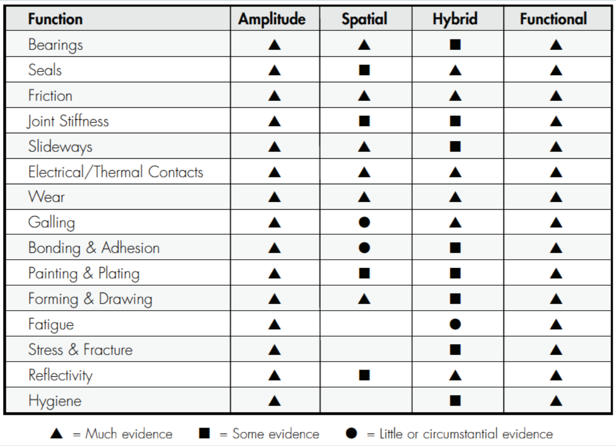
● Roughness

○ Waviness

Figure 7. Stylus analysis settings in Vision64 software.

Utilizing Optical Profiling to Extend Surface Parameter Characterization

With the long history of 2D stylus surface measurements yielding such basic parameters as roughness (Ra), those statistical parameters typically end up being used to measure and control surface finish quality in many markets. Now however, with advanced 3D surface characterization, not only can those 2D parameters get accurately measured, but additional data is available to advance the way a surface gets characterized. These new 3D parameters can highlight large data trends, such as waviness or lay, and additional features, such as a predominance of ridges and scratches, that 2D traces are unable to characterize. With these 3D capabilities, new surface parameters are becoming increasingly used. Known as "S Parameters," these generally categorize amplitude, spatial, hybrid, and functional parameters, as shown in Figure 8. 3D parameters uniquely differentiate not only surface finish and shape, but ultimately the functionality of that surface as well.



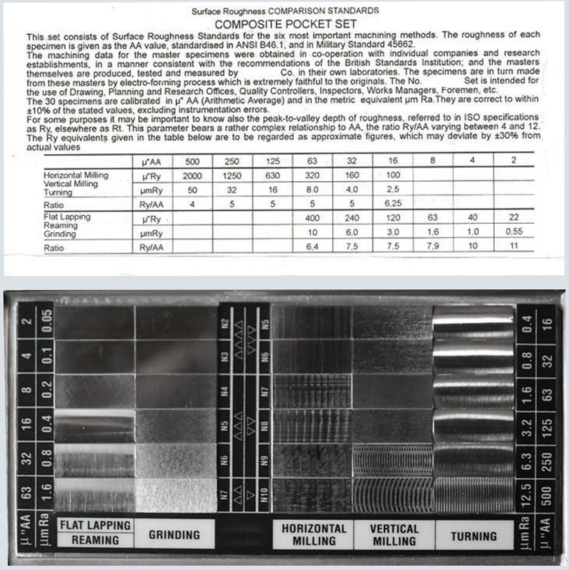
Function	Amplitude	Spatial	Hybrid	Functional
Bearings	▲	▲	■	▲
Seals	▲	■	▲	▲
Friction	▲	▲	▲	▲
Joint Stiffness	▲	■	■	▲
Slideways	▲	▲	■	▲
Electrical/Thermal Contacts	▲	▲	▲	▲
Wear	▲	▲	▲	▲
Galling	▲	●	▲	▲
Bonding & Adhesion	▲	●	■	▲
Painting & Plating	▲	■	■	▲
Forming & Drawing	▲	▲	■	▲
Fatigue	▲		●	▲
Stress & Fracture	▲		■	▲
Reflectivity	▲	■	▲	▲
Hygiene	▲		■	▲

▲ = Much evidence ■ = Some evidence ● = Little or circumstantial evidence

Figure 8. Typical applications for 3D parameters.

Correlating to Fingernail Surface Finish Gages

Recommended measurement practices for 3D optical profiling are being adopted and approved for many industrial markets. The ability to correlate to known traceable standards are needed for most industries trying to achieve traceability and certification. A fairly low-cost approach many companies take is the purchase of a surface roughness standard patch, which can come with a traceable certificate of calibration. These patches have Ra surfaces ranging from 50 nanometers to 13 microns (2 to 100 microinches) and are comprised of different machined surfaces, as seen in Figure 9.



Surface Roughness COMPARISON STANDARDS

COMPOSITE POCKET SET

This set consists of Surface Roughness Standards for the six most important machining methods. The roughness of each specimen is given as the AA value, standardised in ANSI B46.1, and in Military Standard 45662.
The machining data for the master specimens were obtained in co-operation with individual companies and research establishments, in a manner consistent with the recommendations of the British Standards Institution; and the masters themselves are produced, tested and measured by Co. in their own laboratories. The specimens are in turn made from these masters by electro-forming process which is extremely faithful to the originals. The No. Set is intended for the use of Drawing, Planning and Research Offices, Quality Controllers, Inspectors, Works Managers, Foremen, etc.
The 30 specimens are calibrated in µ" AA (Arithmetic Average) and in the metric equivalent µm Ra. They are correct to within ±10% of the stated values, excluding instrumentation errors.
For some purposes it may be important to know also the peak-to-valley depth of roughness, referred to in ISO specifications as Ry, elsewhere as Rt. This parameter bears a rather complex relationship to AA, the ratio Ry/AA varying between 4 and 12. The Ry equivalents given in the table below are to be regarded as approximate figures, which may deviate by ±30% from actual values

	µ"AA	500	250	125	63	32	16	8	4	2
Horizontal Milling Vertical Milling Turning	µ"Ry	2000	1250	630	320	160	100			
	µmRy	50	32	16	8.0	4.0	2.5			
Ratio	Ry/AA	4	5	5	5	5	6.25			
Flat Lapping Reaming Grinding	µ"Ry				400	240	120	63	40	22
	µmRy				10	6.0	3.0	1.6	1.0	0.55
Ratio	Ry/AA				6.4	7.5	7.5	7.9	10	11

Figure 9. Multi-patch fingernail roughness comparator standard.

In theory this appears to be a good low-cost approach for correlation and traceability, but it can cause issues since these type gages are meant to be a "fingernail" comparison standard for an operator to make a rough comparison to the actual surface being machined. An engineer or operator will actually compare the machined surface to the roughness patch by using their fingernail or even just by the visual appearance. When an independent stylus gage calibration was done on one of these patches using a recommended internationally approved measurement practice, it was shown that the new traceable certification values varied significantly from the original certification that came with the patch, as shown in Figure 10. There isn't clear documentation indicating how the original certification values were obtained, but it appears that standardized measurement practices weren't used to certify the gage.

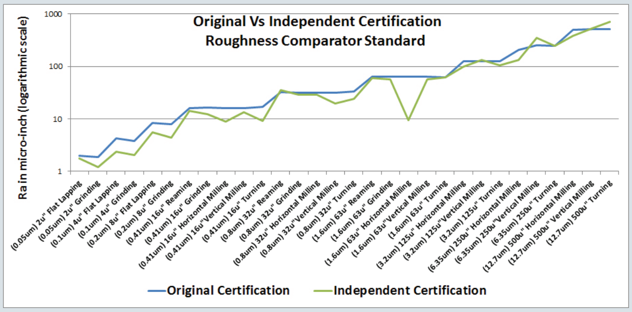


Figure 10. Examples of original versus independent certification.

Once the actual values of the roughness patch are known, the measurement setup parameters used during calibration must also be known so it can be used to duplicate the values on any system, in this case a 3D optical profiler.

When to Use Single Field of View Versus Larger Stitched Image Measurements

Lower roughness surfaces below 254 nanometers (10 microinches) can be measured with a single image on a 3D optical profiler since there typically isn't a manufacturing periodic machining structure or lay to worry about. Lower Ra surfaces also tend to correlate well to contact stylus measurements even without applying the filters the stylus system used. One thing that needs to be considered is that by going to higher objective magnifications, the lateral resolution pixel size gets smaller and more of the microstructure of the surface can be seen. Potentially the contact system can't measure this microstructure, as explained earlier, and could reduce the correlation to the optical system.

When measuring surface finishes with higher Ra values that may contain a periodic machining structure, as seen in Figure 11, the measurement area must be large enough to capture this periodic structure. This would be the same as the sampling length of a contact stylus profiler to meet standardized practices, as discussed earlier.

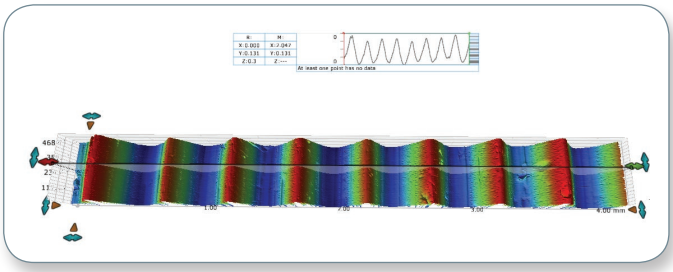


Figure 11. 10x stitched image of a turned surface.

This can be easily done by going to a lower magnification objective to capture this whole periodic structure. The tradeoff here is the lower the magnification of the objective, the lower the objective NA, which also lowers the angle at which the objective can capture light and the angle at which it can measure slopes (similar to large radius contact probe tip limitations). Once the Ra of the surface gets high enough, the surface structure gets very steep and the lower magnification objective may have data dropout similar to the stylus tip radius rounding or smoothing of the surface edges. To resolve this, multiple images are "stitched" together using higher magnification to cover the whole periodic structure area, similar to a stylus system sampling length.

Proper Filtering to Correlate to Contact Measurement

Even after perfoming an independent certification on the fingernail roughness patch, just comparing the 3D optical profiler roughness directly to that certification may not be enough. But once the proper scan length data is captured and the corresponding stylus filters are applied in the 3D optical profiler software, the filtered 3D data can be well correlated to the certified stylus measurements. This can be seen in the Figure 12A, which shows RA data before and after the stylus filter is applied, and in Figure 12B, after the filters were applied and correlated to the independent certification. Slight deviation in the correlation results is attributed to not knowing exactly where the independent certification was performed.

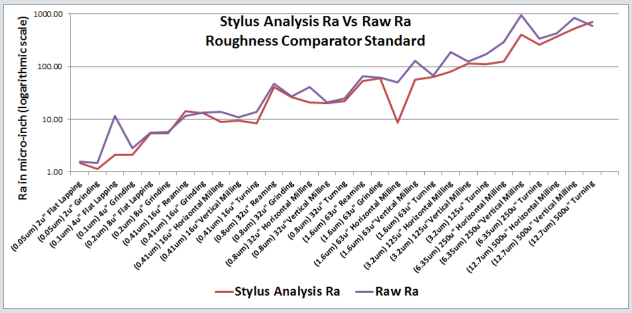


Figure 12A. Optical stylus measurement applied versus raw optical measurement.

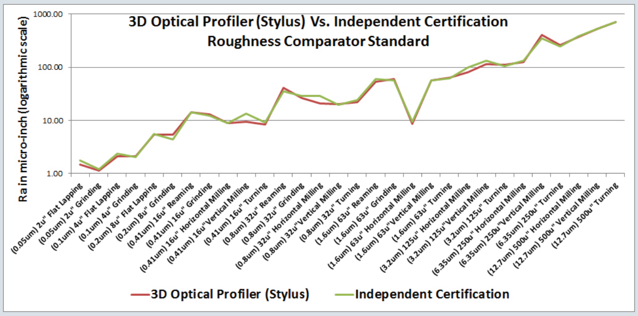


Figure 12B. Optical stylus measurement versus independent certification.

Correlating Measurements to Nationally Traceable Standards

For quality assurance, traceability of surface finish measurement plays an important role in manufacturing for the correlation and functionality of many parts and products. Having the ability to correlate surface finish parameters around the world is done by using standards that are traceable to nationally recognized bodies, such as the National Institute of Standards and Technology (NIST) and Physikalisch-Technische Bundesanstalt (PTB).

For this study, high-precision standards were purchased and then certified at PTB, as seen in Figure 13. The standards chosen are produced for specific surface roughness where the texture and waviness are highly controlled and repeatable across the measurement surface. PTB supplied calibration paperwork with very detailed information about how the standards were certified using a contact stylus system. This certification information is invaluable when trying to reproduce and correlate to these standards using different measurement techniques, including 3D optical profiling based on interference technology.

For all of the standards measured in the study, a Contour

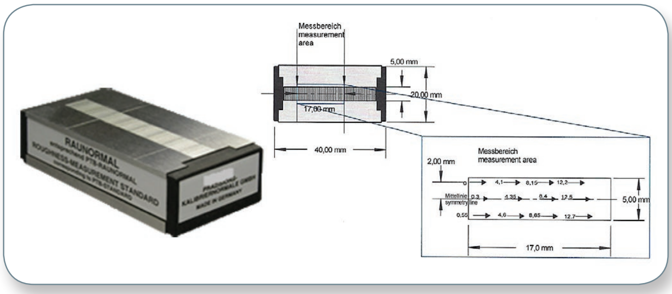


Figure 13. Precision surface roughness standard and measurement locations.

Elite® 3D optical profiler (Bruker, San Jose, CA) was used with a 10x objective and vertical scanning interferometry (VSI) mode. The data was captured in compliance with the PTB certification, making sure the data was captured in the proper location using the proper measurement scan lengths (stitched images) and stylus filtering applied to the measurements. The nine measurement locations were scanned on each standard, then the results were averaged and compared with the error from the PTB certification uncertainty. The results are graphed in Figure 14.

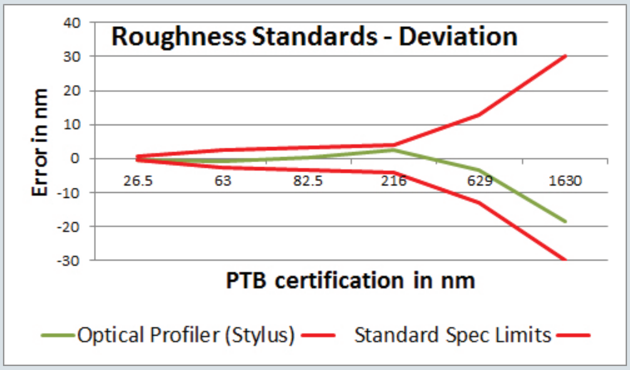


Figure 14. WLI deviation results as compared to certified roughness standards.

As seen in the deviation chart, correlation to nationally accepted roughness standards can be easily achieved as long as the certification process of the standard and proper measurement methods are followed for the 3D optical profiler based measurement.

Conclusion

Advances in 3D measurement techniques have given engineers, process designers, researchers, and quality control professionals a significantly improved way of surface characterization for shape, surface finish, and overall functionality. 3D optical profilers are well established throughout a wide range of industries, from medical implants to aerospace components, and have been shown to outperform other measurement techniques in overall resolution, repeatability, accuracy, and speed. Correlation to stylus measurement systems can be achieved with upfront knowledge of the surfaces being measured and the setup of the stylus tool used to measure those surfaces. Some minor correlation differences are expected due to measurement location and texture coherence/speckle effects, but these can usually be accounted for or tracked via a correlation factor, if necessary. The addition of the 3D surface S parameters greatly extends the degree to which surface analysis can uniquely characterize both sample shape and function. The result is the most radical improvement in measurement data since the early introduction of 2D stylus-based profilometry.

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