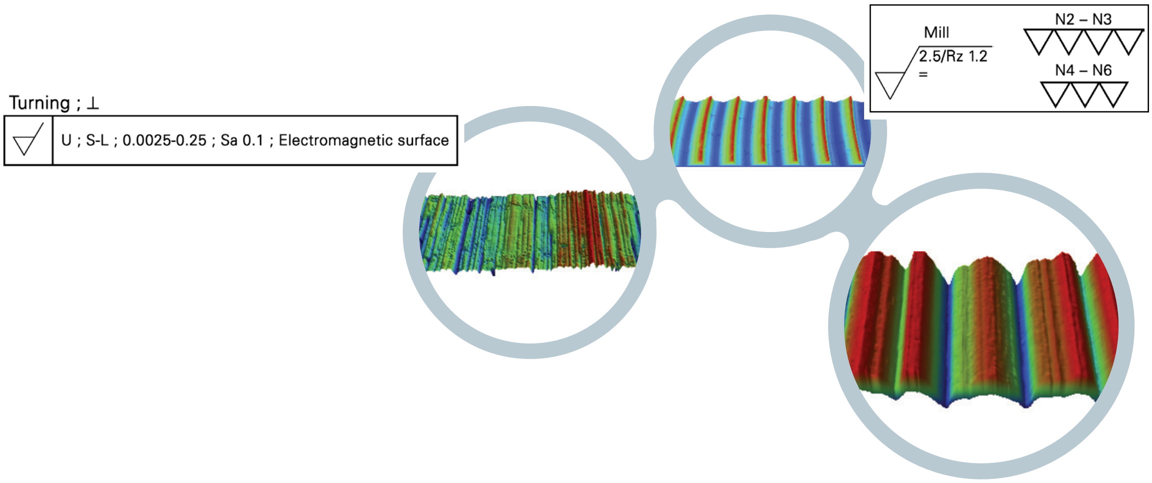

Application Note #575

Advantages of Measuring Surface Roughness with White Light Interferometry

The concept of measuring surface roughness originated nearly a century ago as a means to prevent uncertainty and disputes between manufacturers and buyers. Now, it has become a common identifier used throughout industry for validating manufacturing processes, confirming adherence to both internal and regulatory specifications, and guaranteeing quality and performance of end products. Subjective judgements of quality based on naked eye observation or fingertouch feel of surfaces has steadily been replaced by unbiased metrics and well-defined formulas.

The first parameter developed for these endeavors was mean roughness (Ra), which for a number of reasons, is still a primary reference parameter used today. First, mean roughness is easy to work out, even in an analogic way, which not only was important in early implementation across a variety of industries, but also makes it a convenient and quick method for current characterization. Second, the Ra parameter is a robust calculation that averages outlier data and provides constant results irrespective of the roughness pattern. This is critically important to not only assist with a wide variety of industrial manufacturing processes, but also to provide a solid baseline for process improvement.

Adoption of Ra as a key parameter to qualify surface roughness relies on defined standard samples (standards) of the desired profile measurement. These are relatively easy to manufacture for a single line profile and are commonly used to assess if a roughness measurement system is properly calibrated. This ensures that the Ra value given for a specific surface is linked back to a well-established reference value. Such standards also help to achieve a common reference across multi-industrial sites and provide tool-to-tool correlation in multi-metrology systems. While these standards were originally designed for the single-line measurements of stylus-based profilers, they are able also to confirm that both contact and non-contact areal-based profilers acquire the correct results.

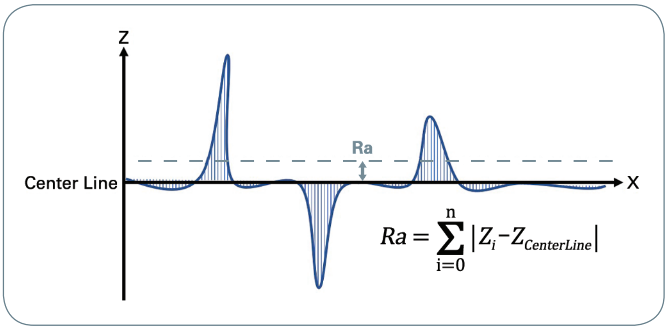

Figure 1. Illustration of mean roughness calculation.

This application note discusses the use of mean roughness measurements with white light interferometry (WLI) optical profilers. Spatial filters are explained, as well as some of the normative standards requirements from ASME B46.1-2009,[1] ISO 13565-1[2] and JIS B 0671-1.[3] Main technical reasons for WLI selection are covered as well as the advantages and areas of applicability of the full areal measurement standard from ISO 25178-2.[4]

Roughness and Spatial Filtering

In manufacturing, products are defined through key dimensions summarized into technical drawings. Roughness is one specific critical parameter that defines how much a surface measurement deviates from a specified shape or form, with height variation within the millimeter lateral range. Larger fluctuation in topography is part of another parameter, waviness. The surface of a product is the aggregate of form, shape, waviness, and roughness, all defined to a desired volume. In this respect, roughness can only be worked out after the proper selection of spatial components, excluding shape, form, and waviness. Roughness measurements always include step, where shape is removed, either directly via a physical skid (as with some stylus profilers), or via post-processing (e.g., high-order polynomial fitting and/or spatial filtering).

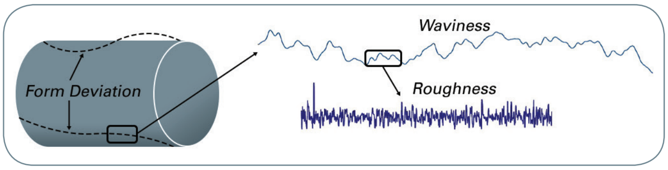

Figure 2. Determining roughness for a cylindrical part.

In the latter case, long-range topography fluctuations or equivalent low spatial frequencies are leveraged out through a high-pass filter, which only allows fast topological variation to pass through. Vice-versa, short rapid variation on a profile more often indicates the presence of noise, which should not be considered for a roughness measurement. In such cases, the high spatial frequencies are excluded through a low-pass filter. Thus, raw measurement profiles go through band-pass filters for lower and higher spatial limits. In ISO 4287 and ASME 46.1 norms, those boundaries are defined as λc and λs cut-off parameters.

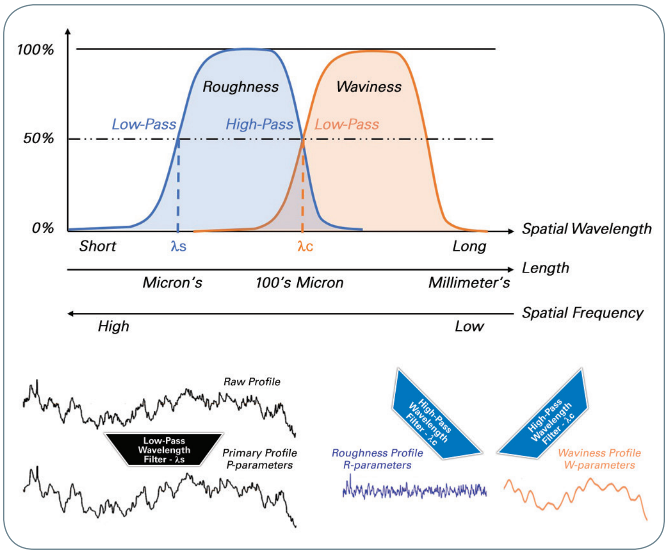

Figure 3. Spatial filter definition with associated derived parameters and resulting profiles.

While filtering is an essential part of measuring roughness, it should be kept in mind that filters can also distort measured topography. For example, the traditional use of RC filters were well-known for triggering edge effects that required the use of exclusion bands at the beginning and end of profiles to remove spurious data. RC filters are also prone to distort topography around sudden height variations, such as peaks or pits. Therefore, this filter has been mostly replaced in current usage by more reliable filters, such as Gaussian and spline-phase-compensated filters. The more recent use of areal roughness has initiated the need for even more advanced filters, such as the Robust Gaussian Filters,[5] which are part of the ISO 25178 norm. These filters provide a unique advantage in avoiding edge effects. This allows a roughness calculation by effective removal of waviness across the entire measurement field while accurately capturing fine variations in topolography.

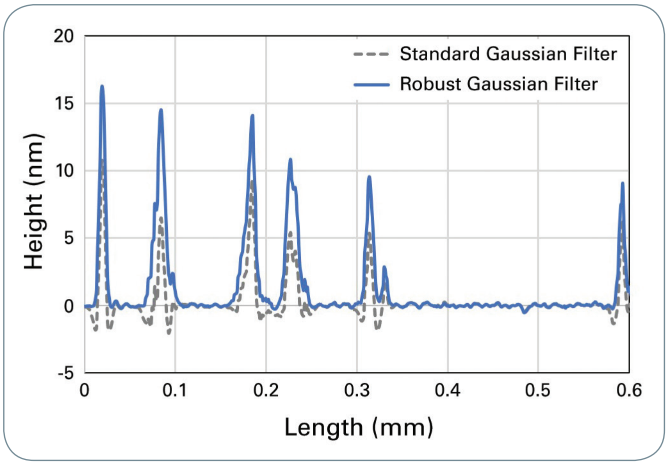

Figure 4. Plot showing the advantage of a spatial filter.

Profile Versus Areal Measurements

For almost a century, stylus-based profiles have successfully captured mean roughness and assessed the quality of parts. Common turning, milling, and other CNC machining processes all leave well-defined direction where roughness occurs. In such cases, dragging the stylus perpendicularly to the main machining traces provides reliable and precise measurement of a surface's texture. This type of measurement is now referred to as a 1D type, where height (Z) is expressed versus scanning length (X).

Over the last two decades, however, requirements for increased manufacturing efficiency and both energy and cost savings have driven a higher level of complexity for surface metrology. Surfaces are now engineered to serve specific purposes, making the roughness parameter an even more critical parameter for most precision-engineered parts. Surfaces are textured in multiple directions to increase performance (e.g., with a lower coefficient of friction), or to improve lifetime or wettability (to name just a few). All these processes are challenging to assess with a single-line profile, making multi-site measurements and a better statistical approach mandatory.

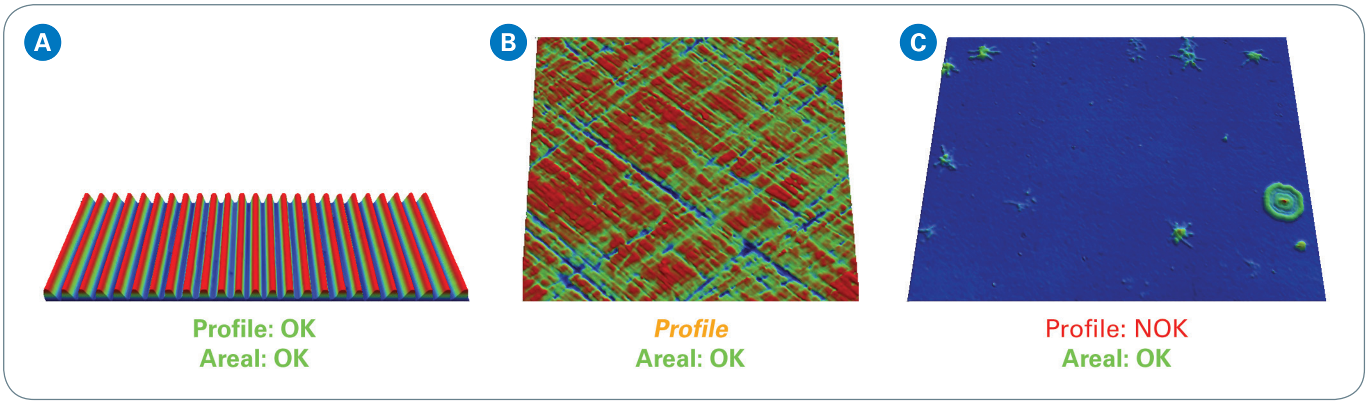

Figure 5. Three types of surfaces showing different applicability for profiler or areal topography measurements: (A) profile roughness standard; (B) cross-hatch texture on bore cylinder; and (C) defects on an optical window.

With these rising limitations in pure 1D roughness measurements, full areal roughness metrology, known as 2D measurements, have become the most common means of characterizing surface roughness. These measurements plot vertical height versus X and Y directions. The first techniques available were also based on stylus profiler capabilities, combining multiple adjacent lines into an area. The main drawbacks for this approach were the long measurement times, usually an hour or more to achieve high lateral resolution in both directions, as well as the inherent fluctuation between each line due to mechanical drift. In the 90s, several groups succeeded in utilizing optical microscopes to measure topography, based on interferometry techniques.[6] This enabled fast (seconds to minutes) non-contact roughness measurements. Since then, areal roughness measurement techniques have expanded to include confocal,[7] focus variation,[8] and digital microscope approaches.

These techniques all capture the full field of view and work out a dedicated height position for each pixel of an image. These techniques are now referred to as 2D (area). It should be noted that there are also 3D techniques that measure full volume, including re-entrant and porous surface (e.g., confocal X-ray tomography). However, these techniques excel at different parameters than surface roughness. With a 2D or areal measurement, it becomes much easier to capture surface texture in all directions, as well as to spot any random defect along a surface. It also captures a larger field, which makes measurements more representative of overall surface texture, as well as more robust through the higher amount of statistical data available.

In modern industry, 1D and 2D measurement techniques co-exist. For standard manufacturing processes that leave a single texture orientation, mean roughness can easily be captured through a few profiles. If a texture has two or more orientations, both stylus profiling and areal measurements are valid; with stylus profiling requiring multiple lines, more time, and further statistical analysis to accurately present the surface. Finally, in the case of random and/or a complex engineered texture, optical areal measurement becomes mandatory to properly evaluate the surface.

White Light Interferometry Profiler

Due to the increased complexity of much manufacturing today, non-contact areal profilers are widely utilized to measure roughness in both R&D and production environments. Many design variations exist, but they commonly share a design with a dedicated rigid structure that serves as a platform for high-end objectives and digital cameras. They also share the fact that lateral and vertical resolutions are objective dependent, which has led to the common use of highly resolutive objectives with short working distances for best vertical resolution. A major exception to this trend is the WLI-based profilers, where vertical resolution not only becomes independent from the objective but also uniquely reaches sub-nanometer levels.

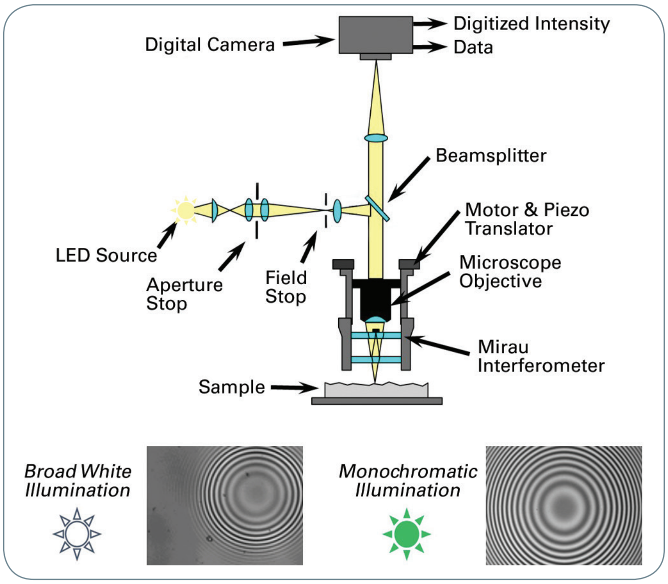

Figure 6. WLI optical implementation with display of different Moiré pattern versus illumination.

A WLI profiler utilizes interferometric objectives that reveal the sample surface via a moiré pattern only when proper focus is reached. As the depth of field for the moiré presence does not exceed ±0.5µm due to the limited coherence length of white light illumination, the focal plane can be easily worked out through finding the maxima within a couple of nanometers. This sharp determination of focal plane relies entirely on moiré and is independent from the objective, which guarantees nanometer precision even with low-magnification objectives (e.g., 1x, 2.5x, or 5x). There are several positive consequences of this approach:

- Long-working-distance objectives can be used without compromising vertical resolution to access specific or recessed locations on a complex part;
- Ease of use is increased with the extra safety margin between objective and surface, as well as with the ability to target challenging locations;
- A mirror can be inserted along the focusing beam, deflecting the optical path to measure vertical walls with higher precision;
- If low lateral resolution is needed, a single acquisition at low magnification covers a wide range (100mm^2), making rapid detection of defects possible, or permitting high-throughput flatness control;
- Stitching can be used to combine high lateral resolution over even wider areas;
- Metrology assessment and budget allocation become easier since all objectives have the same vertical precision.

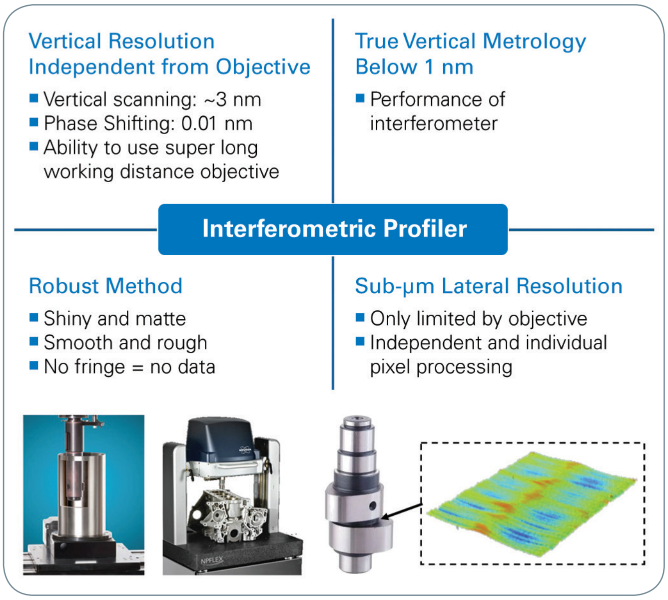

Figure 7. Attributes of WLI metrology.

A WLI-based profiler not only complies and is listed as an appropriate technique for areal norm ISO 25178-204:2013, it is also, due it its unique vertical resolution, being used by major reference metrology laboratories (NIST, PTB, NPL, et al.) to calibrate for artifacts. Based on this work, some advanced WLI profiler designs utilize a direct reference to a stabilized HeNe laser[9] for automatic and self-calibration purposes.

Roughness Calculations

The ISO 11562-1997, ASME B46.1 and JIS B 0632:2001 standards clearly define measurement conditions, as well as filtering, for surface profiles. Prior to the roughness calculation, the raw profile is corrected for shape. Then it goes through a low-pass filter determined by cut-off λs to obtain the primary profile, P. Roughness parameters are worked out after further high-pass filters, defined by cut-off λc, to remove waviness. All R parameters are derived from this roughness filtered profile. The filters are defined by mathematical function; most often Gaussian or spline-phase corrected. For periodic profiles (e.g., milling, turning, etc.), both cut-off parameters are set to expected mean roughness for random surfaces or with spacing between peaks (see Table 1).

From the cut-off values, standards derive the exact measurement travel (Lt), which includes evaluation length (Lm) extended by pre- and post-lengths. In the case of a Gaussian filter, pre- and post-lengths correspond to λc/2 length to reduce influence of potential mechanical backlash at the start and end of a scan, as well as filter edge effects. This precaution is not necessary for modern optical profilers and robust Gaussian filters. The evaluation length corresponds to a series of five sample lengths; itself being equal to the λc cut-off value. Such stringent conditions are necessary not only for extraction of relevant information from the complete profile, but also to ensure seamless comparison between different instruments. Mean roughness results directly correlate with selected cut-off values as well as with the spatial filter used. Any change of measurement parameters conversely modifies the roughness output: whenever inter-comparison between different measurement systems is engaged, all filtering parameters must be identical.

Periodic Profile	**Non Periodic Profiles**		**Cut-off**		**Cut-off Ratio**	**Evaluation Length**	**Stylus**
Spacing Distance RSm (mm)	Rz (μm)	Ra (μm)	λc (mm)	λs (μm)	λc/λs	Lm (mm)	Radius (μm)
>0.013 to 0.04	to 0.1	to 0.02	0.08	2.5	30	0.4	2
>0.04 to 0.13	>0.1 to 0.5	>0.02 to 0.1	0.25	2.5	100	1.25	2
>0.13 to 0.4	>0.5 to 10	>0.1 to 2	0.8	2.5	300	4	2 (5@Rz>3μm
>0.4 to 1.3	>10-50	>2 to 10	2.5	8	300	12.5	5 or 2
>1.3 to 4.0	>50	>50	8	25	300	40	10, 5 or 2

Table 1. Measurement and spatial filter conditions versus expected profile roughness.

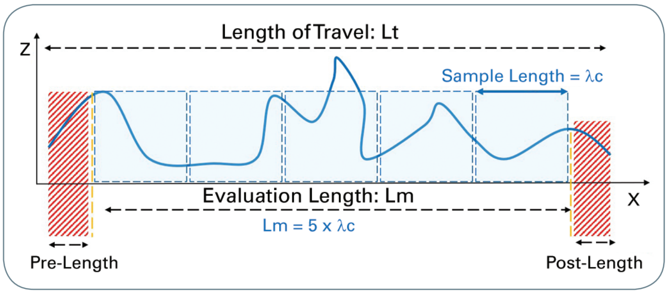

Figure 8. Details on total measurement length.

For areal measurement, ISO 25178-2 is the sole standard for roughness calculation. This norm leaves selection of cut-off values and evaluation length to the operator but dictates step-by-step filtering of the raw surface. Raw surface data acquired by the profiler first gets low-pass filtered (digital or spatial) to remove noise and outliers. The result is the Primary Surface value. Most common spatial filters are based on Gaussian Regression, or Robust Gaussian, which provides a better response on sharp transitions and has almost no effect on borders. The Primary Surface is further processed with shape removal to create the S-F Surface value. To remove waviness, an extra high-pass filter can be used to produce an S-L Surface value. Users can further crop borders to obtain the scale-limited surface and work out roughness parameters. In such conditions, the areal roughness standard does not distinguish parameters: they are all labelled as S parameters. ISO 25178, however, does require listing the whole post-processing chain prior to displaying parameters, such as cross-check control. The same applies to roughness specifications on technical drawings, where exact measurement conditions must be clearly labelled.

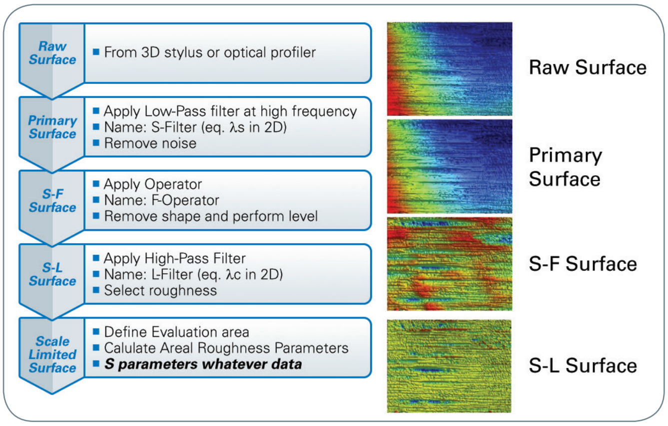

Figure 9. Step-by-step processing for areal roughness.

Measurement of Roughness Standard with WLI

One of the core applications of WLI-based profilers is measuring sub-micron roughness and surface texture. The technique's unique sub-nanometer vertical resolution, combined with its large field of view and long-working distances, make it suitable for metrology of all precision-engineered parts, ranging from forged flat metal to complex/curved surfaces, such as gears or bore cylinders. In addition to this flexibility, the WLI optical profiler metrology capability benchmarks to certified roughness standards. Here, we investigated nine standards from three different manufacturers (Rubert,[10] Halle,[11] NPL[12]).

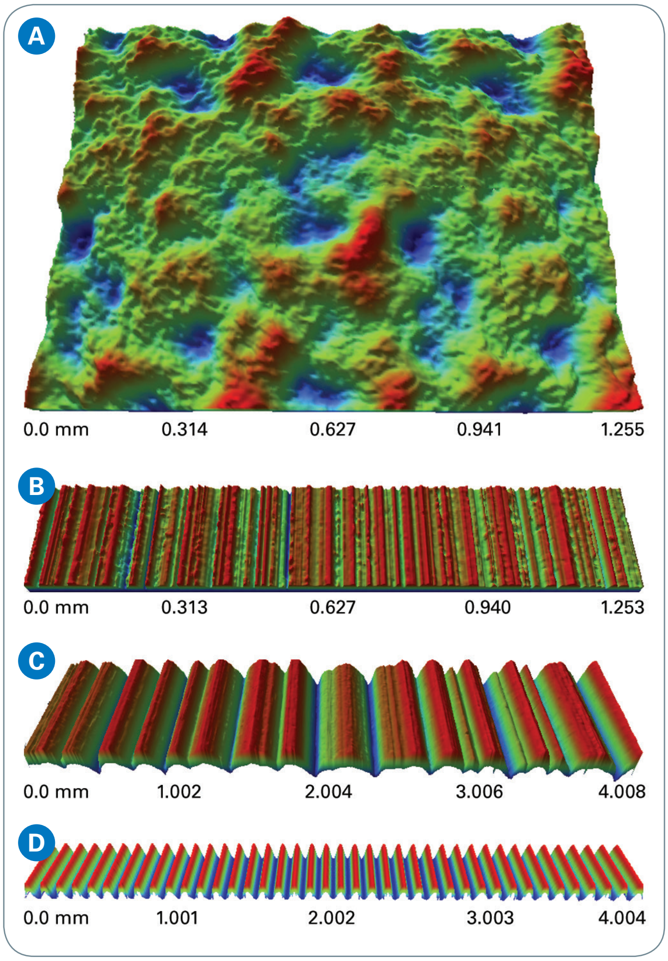

Figure 10. Topography rendered in 3D view of different roughness standards: (A) areal; (B-C) random profiles; and (D) sinusoidal profile.

The goal was to cover extensive lateral and vertical ranges to ascertain metrology capability across a wider number of applications. This approach also offers comprehensive assessment for linearity performance over the vertical range. One areal artifact was also part of our evaluation to represent a real case for this native areal measurement method.

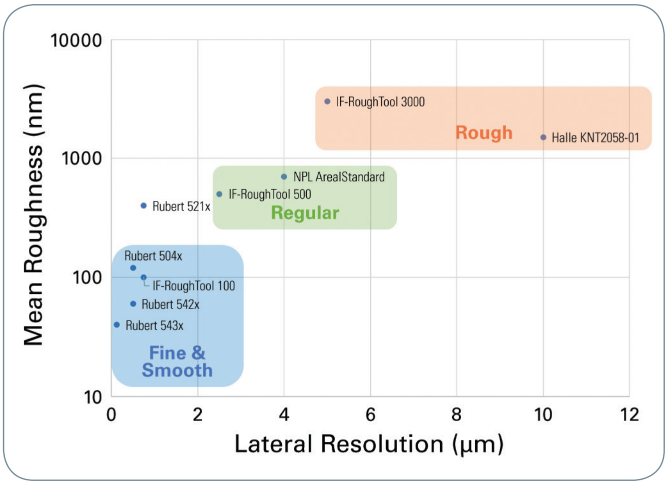

Figure 11. Plot of nominal mean roughness versus required lateral resolution.

Technical Considerations

Regular 1D roughness standards are primarily designed for stylus-based profilers. In that respect, lateral resolution capability does not depend on scan length but rather on aspect ratio and depth of the surface features. On the other hand, an optical profiler has inherent changes in lateral resolution whenever a low-magnification objective is in use. It is consequently important to select an objective that achieves a lateral resolution better than the λs cut-off. Operators must also ensure that camera sampling is at least twice the optical resolution to effectively achieve the expected lateral resolution. Otherwise, lateral resolution becomes limited by pixel size. Once the objective and zoom lens are properly selected, the evaluation length is ensured either by single acquisition or by the stitching of multiple fields of view.

Here, 5x, 20x, 50x, and 115x objectives were used. Lower magnification (5x) was utilized for rougher surfaces that required less lateral resolution and longer evaluation length, while the 115x objective was critical to resolve the finest patterns.

All data first underwent a 4th order polynomial removal before going through a Gaussian Regression band-pass filter. Cut-offs were selected per the ISO 11562-1997 norm and settings from the standard certificate. Final roughness extraction consisted of separating the areal image as a series of single-line profiles for which mean roughness (Ra) was worked out. Results not only showed the average mean roughness along all profiles, but also indicated fluctuation of the Ra value, one sigma deviation.

To address precision, measurements were repeated 30 times over each roughness standard in a fully static way. This follows the recommendation from the Guide to the Expression of Uncertainty in Measurement (GUM).[13] Coverage factor k=2 was chosen, representing 95% of results for a purely random Gaussian distribution.

Results

All mean roughness results are summarized in Figure 12, plotting measured Ra value versus certified value in log-log scale. In assessing the quality and consistency of the WLI optical profiler, there is great correlation over two decades, from sub-100 nanometers to over a micron mean roughness. Error bars are represented for each result using $\pm 2\sigma$ dispersion from static repeatability. However, they are hardly visible since, on average, they are below 1% of the result. This emphasizes how repeatable the WLI profiler is.

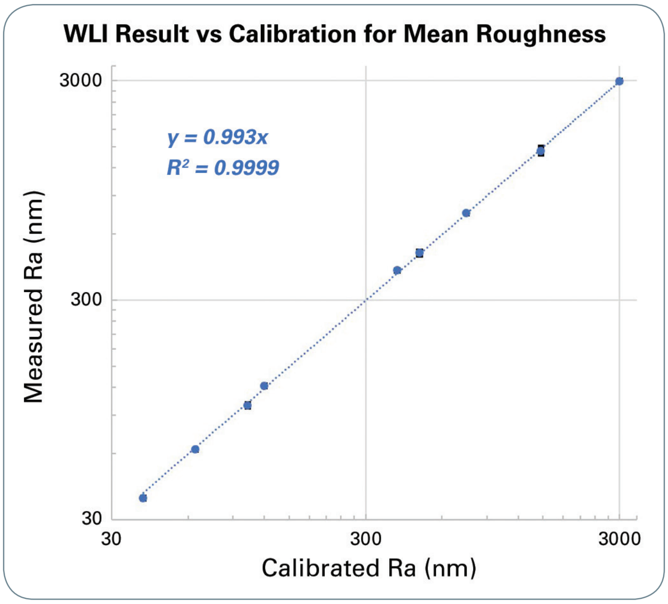

Figure 12. Measured mean roughness by WLI versus certified nominal value in log-log display.

Further validation of results relies on the comparison between measurement of the dispersion interval and the confidence interval from the standard certificate. Figure 13 illustrates different configurations and indicates whether a decision can be made from the data results. Since the dispersion range always lies within the uncertainty of the standard, all the results obtained with the WLI profiler are positively assessed. Data prove the accuracy of the WLI profiler measurements across the entire range of the available roughness standards.

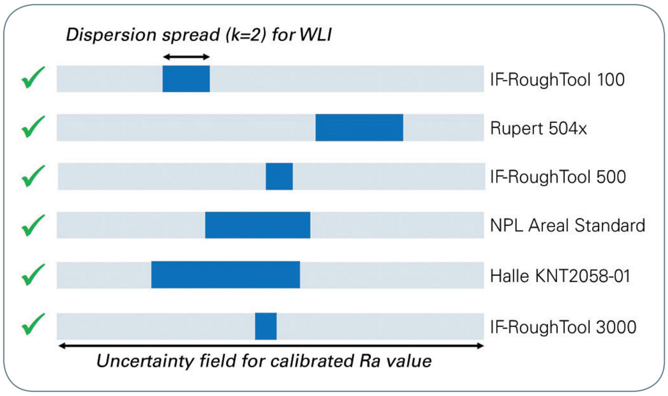

Figure 13. Mean roughness results assessment versus certification.

Interestingly, the WLI profiler provides reliable data at both extremes of the tested spectrum. On the rougher side, a low-magnification 5x objective delivers precise measurement. Robust algorithms for topography extraction from optical data, together with high-power illumination, provides a good ability to measure surfaces with rough, steady slopes. This extends the capability of the WLI profiler to tens of microns roughness, enabling the measurement of additive manufactured parts for instance. At the other extreme, sub-micron fine pitch can be clearly resolved by a WLI profiler, providing adequate lateral resolution. This can be seen by a direct comparison of WLI profiler measurements with those of an atomic force microscope (Dimension Icon, Bruker). Figure 14 nicely exhibits the correlation between section profiles made with the two techniques. A high numerical aperture 115x objective, together with sub-nanometer vertical resolution and an advanced super-resolution algorithm, expand the transfer function of the optical profiler beyond micron lateral size.

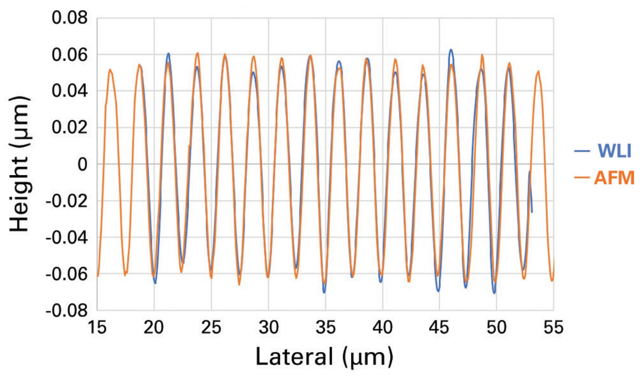

Figure 14. Profile comparison on sinusoidal standard between WLI optical profiler and AFM.

Conclusions

This application note has provided a comprehensive overview on how surface roughness has evolved as a key manufacturing parameter, from technique capabilities to normative guidance on both profile and areal measurements. The WLI-based optical profiler measurement examples against certified roughness standards show perfect correlation with certified values. With a dispersion range below 1% and a precise mean value the WLI profiler is capable of measuring mean roughness over 2 decades (from 3µm to 40nm). WLI profilers also have a proven ability to measure steady, rough slopes, as well as to achieve sub-micron lateral resolution, all while maintaining extremely precise vertical measurement. These factors indicate that WLI profiling will continue to play an integral role in the ever increasingly stringent R&D and manufacturing requirements for next-generation industrial products.

Acknowledgements

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