A New 3D Surface Characterization Method Is More Quantitative and Reproducible Than Traditional Peening Metrology

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ABSTRACT

Current metrology methods of shot peened surfaces have many shortcomings. 2D stylus methods are directionally sensitive, can't measure corners or edges, often difficult to setup, and offer small overall coverage. 3D microscopes have high resolution and good areal coverage but lack on portability and can take significant time to capture a single data point. This paper presents a high-resolution, extremely portable 3D optical measurement system for comprehensive, accurate, fast shop floor assessment of shot peen coverage. A variety of component measurements will be presented along with studies on accuracy, repeatability, and reproducibility in real-world environments.

Keywords: structured light, polarized structured light, 3D measurements, dynamic interferometry, surface inspection, shot peen, surface roughness, S-Parameters, R-Parameters

1. INTRODUCTION

Surface structure, or surface roughness quantification is a well-known technique for aiding in the qualification of a peened component. This paper will not attempt to correlate surface parameters (S-Parameters) to peening parameters but instead, assume a correlation exists already, based off many published works, and attempt to show that 3D methods, especially portable solutions, are much more comprehensive, repeatable, and reproducible for a given surface structure on the shop floor compared to other methodology traditionally used.

Optical metrology based on interferometry, fringe projection or speckle methods[1] has become indispensable to quantify a variety of surfaces in the production of precision machined parts. The choice of parameters for testing surfaces is large: the field-of-view, lateral and vertical resolution, and the depth of field all can be suited to a particular application. Shop-floor, 3D-measurements of key parameters saves time and improves accuracy. Parts do not have to be moved to a measurement laboratory for characterization, and 3D characterization eliminates the errors usually associated with conventional 2D trace methods. Such systems are also necessary because some objects, such as turbine blades, shafts, or engine cowlings, are simply too large to be tested using a laboratory-based stylus or 3D microscope system. Additionally, 3D optical measurement systems provide non-contact measurements, and the most advanced systems can be immune to vibrations, allowing hand-held operation. Although other fast methods exist[2,3], they often are limited to flat samples, require multiple cameras, or have limited resolution, making the systems unsuitable for hand-held, shop-floor use.

2. CURRENT MEASUREMENT METHODS OF SHOT PEENING ON MACHINED SURFACES

Assessing the peening or surface roughness on machined parts on the production floor commonly relies on visual or stylus-based methods. Alternatively, these assessments can rely on a lab-based microscope system which requires a small sample, often not the part itself, and can take hours to provide any meaningful data. While these methods are commonly practiced, they are often slow and/or difficult to duplicate. Much faster, quantitative measurement can be achieved via a microscope using rubber, replicast material, representative material, or a small section cut off the real part. This process is super time consuming, potentially destructive of samples, and not very reproducible.

Stylus based systems can provide some shop-floor capability for shot peening or general roughness measurements, but again only over a single, 2D line. This can lead to large variations in results from operator to operator or trial to trial even on the same part, as there are both local variation sin shot peening depth and larger variances due to the overall part geometry. They also typically have lateral and vertical resolutions of tens of micrometers and cannot measure fine geometries. This system additionally suffers from alignment errors, is easily affected by vibration, and often cannot measure over sharp edges without breaking the stylus tip. Setup time on a complex part can be quite long as the stylus tip cannot pass over an edge without risk of breaking and finding a vibrationally-stable measurement location on a complex part is often quite difficult. Due to setup time and the need to take multiple scans to have statistically meaningful data, it can take more than 30 minutes to achieve consistent results.

Fringe projection systems can provide the needed precision and portability required for shop-floor characterization of shot peened surfaces. Precision of a few microns is readily achievable when they are designed to have an effective wavelength of the fringes of a few hundred microns. However, typical fringe systems also have limitations. This next section will quickly review the limitations of most fringe projection/structured light setups.

Fringe projection systems consist of three parts: fringe generation and projection on the object, fringe detection, and fringe processing and analysis. Fringe generation and projection used to rely on the projection of a Ronchi grating onto the object while introducing some defocus to make fringes more sinusoidal. Digital micromirror projectors (DMD) or liquid crystal displays (LCD) are now the most common due to their flexibility. The programmability of these systems allowed for the development of techniques based on projection of other than sinusoidal or binary fringes, mainly grey-code light projection or structured light of various spatial patterns. But DMD, and LCD-based systems are not well suited for projection of high frequency fringes that have an effective wavelength of a few hundred micrometers due to limitations in the number of pixels of the devices. Thus, such systems do not have sufficient vertical resolution to assess most shot-peened surfaces with the required accuracy and repeatability. Interferometrically-generated fringes have no such limitations.

The detection system is commonly a CCD or CMOS array for most all fringe-projection systems. However, fringe processing and analysis typically require projection and detection of a few phase-shifted fringe patterns over multiple camera frames. These systems are therefore sensitive to vibration since lateral motion will mean one pattern is not aligned with the next. Single-frame fringe projection systems typically rely on fringes with a high carrier frequency, which in turn are analyzed using Fourier or similar transforms based or spatial carrier phase shifting method. Those methods restrict the range of measurable slopes and discontinuities on the object. However, with a specialized camera using micro-polarizers, a single-frame system without severe slope and discontinuity limits can be achieved.

3. POLARIZED STRUCTERED LIGHT (PSL) METHOD

Systems based on fringes generated by interference with polarization interferometry combined with a detector with a micro-polarizer array for single camera frame detection are well-suited to hand-held shop floor measurements. Four phase-shifted sets of data can be acquired simultaneously.[6] This single camera method is much more compact and easier to align than traditional systems based on three cameras with polarizers, which also can be used for simultaneous shifted fringe detection in polarization systems. By selecting information from pixels of the same polarizer rotation, the phase-shifted images can be displayed and analyzed using, for example, four-frame, phase-shifting interferometry PSI algorithm[7]

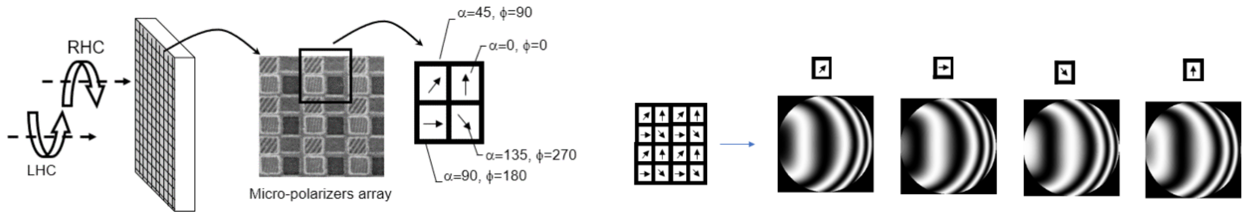


Figure 1. Left, Instantaneous phase shifting method for two orthogonally polarized wavefronts (Right-Hand Circular and Left-Hand Circular) by a camera with micro-polarizer mask with polarizers oriented at angles 0, 45, 90 and 135 degrees and introducing 0-, 90-, 180- and 270-degrees phase shift between beams. Right, fringes extracted for polarizers of the same angular orientation.

To apply this method to fringe projection, the fringes must be created by the interference of two orthogonally polarized beams at the surface of the object. This can be achieved in different ways, such as a Twyman-Green interferometer, Wollaston prism beam splitting, or a special polarization grating. Because the wavefronts are orthogonally polarized, the fringes are not observed on the object with the naked eye but only if the polarizer is placed in front of the detector.

Some caution and system calibration are needed in systems with polarization. For example, if polarization deviates from being circular, some phase ripple may be present in the measurement. Thus, it is important that the polarization is close to being circular. Another potential source of error may be a difference in transmission of the micropolarizers at different polarizations; such differences, however, may be corrected via calibration. Other error sources will vary with the method used for splitting the light into two orthogonally polarized light beams. Another source of error is the variation in brightness across the sample and if this variation is calibrated the error will be significantly reduced. Sample brightness variation also comes into play when determining the optimal projected fringe frequency, since fringe frequency should not be higher than the brightness variation frequency but should not be too low either as it would decrease vertical resolution.

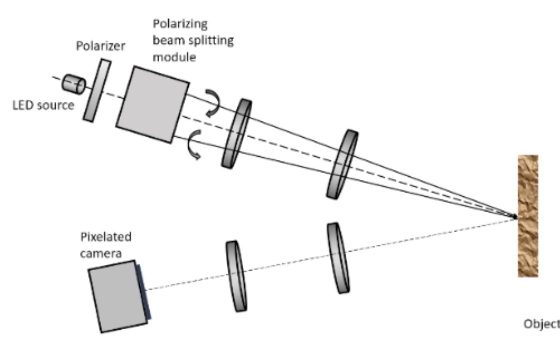


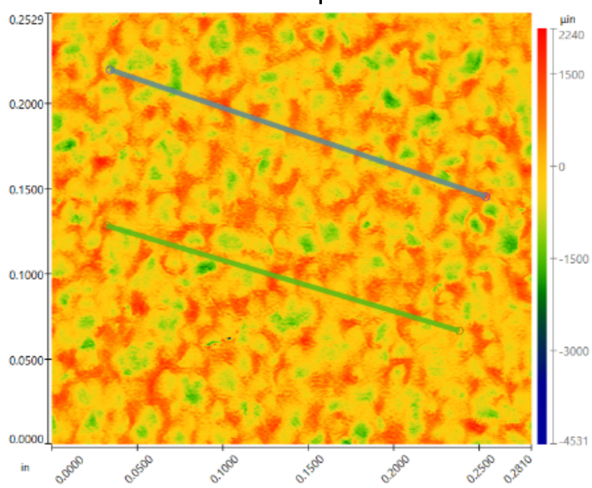
Figure 2. Schematic diagram of single frame polarized structured light system.

The newly developed single shot method based polarized structured light seems to be fitting very well needs of the niche market in aerospace, auto and ship building industry and other large precision mechanical parts builders where testing equipment needs to be brought to the sample.

4. 3D SURFACE CHARACTERIZATION AND MEASUREMENT OF SHOT PEENING

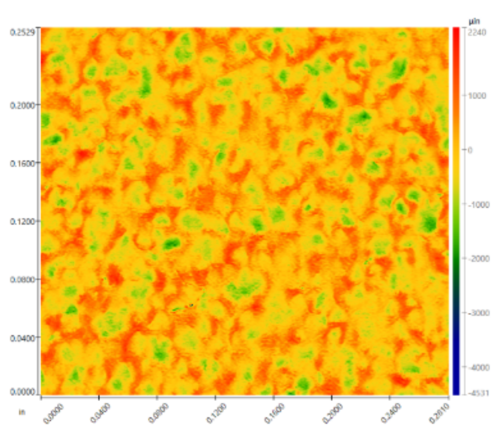
S-parameters, the 3D version of the more commonly known 2D R-Parameters, are ideally suited for determining characteristics of a surface which can be correlated to a given function for use in many applications. Ra of a single trace is problematic for several reasons. First, vastly different surface structures can have similar Ra, as it doesn't consider the spatial scale of any height variations. Secondly, as mentioned previously, traces are directionally dependent and also provide very small overall sampling of the part. Sa, the 3D equivalent to Ra, provides roughness information across the entire 3D measurement, so provides information on a larger area without having to change any drawing parameters. However, in the case of shot peening various S parameters such as those relating to bearing ratio (Smr, Smc, Sdc…) or the ratio of peaks to valleys (Ssk, Sku, Spk…) will likely eventually be adopted by industry since they can correlate with the function of surfaces and not just provide a control number that doesn't relate to how a surface performs such as Ra/Sa. For now, Sa can be logged alongside all the other comprehensive 3D parameters to 'fingerprint' surfaces and ultimately when problems arise that extra information can be used to determine which parameters can help control those problems.

Single trace techniques used to calculate roughness are rife with limitations. The first one is the limited information gleaned from just one trace. Depending on the location, roughness can vary significantly as readily illustrated below using various traces across a 3D shot peened surface. This example was taken on a comparator standard and ideally should be as even as possible across the whole area. Below the error varies between 2 and 30 percent, depending on location of trace relative to nominal result from comparator manufacturer.



Result	Angle (deg)	ROC (in)	Ra (µin)	RMS (µin)	PV (µin)	Rz (µin)
Line Cursor 1	0.4368	0.1042	492.3	592.7	2955	2909
Line Cursor 2	-0.1349	0.2541	343.9	467.4	2968	2931

Figure 3. R_a varies significantly between 344 and 492 micro-inches, as shown in the table below the surface map. Note: the specified roughness for this sample location, a GAR MICROFINISH COMPARATOR (SH-6), is 500 micro-inches R_a. This demonstrates how the location of a 2D trace can have a large impact on the results.



Surface Stats	
Sa	433.0 µin
Sq	542.5 µin
Ssk	-0.04162
Sku	2.977
Sz	6771 µin
Sv	4534 µin
Sp	2237 µin
Sal	0.006176 in
Str	0.8415

Figure 4. Using same data set as in figure 4, 3D results are displayed along with the S-Parameter values. S-parameters are calculated automatically based on the full field of view irrespective of orientation, clocking, or any operator input. 3D analysis of roughness, by its nature, is much more reproducible than 2D trace analysis.

3D Data also can show clear differences visually. See below an example of various peened surfaces and their 3D surface maps.

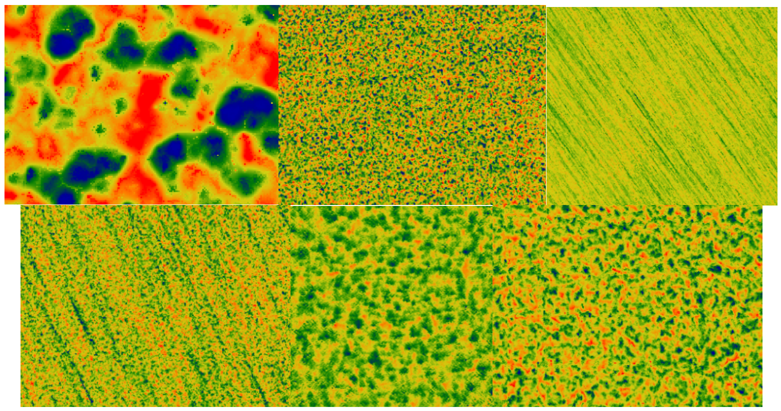


Figure 5. With a variety of peened samples, 3D visual results can vary dramatically.

Finally, the repeatability and reproducibility of 3D metrology is best seen via a gauge study. A gauge study was performed using, for an example of shot peening, a GAR SH-6 MICROFINISH COMPARATOR® Surface Finish Scale. Each of 6 locations was measured 10 times by 3 different operators. Nominal surface roughness varied from 32 to 1000 micro-inches. See results below:

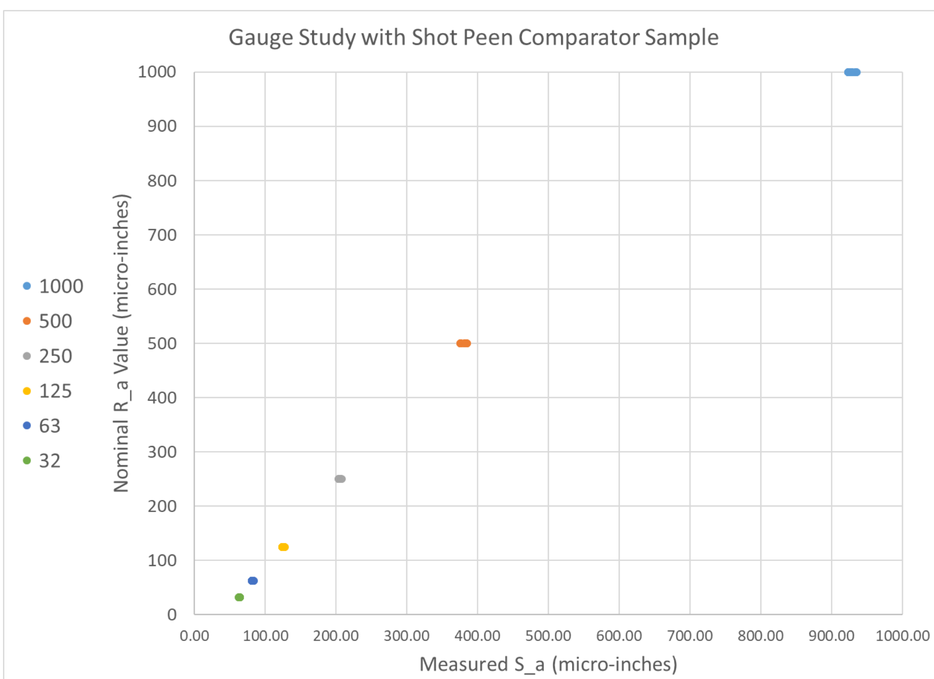


Figure 6: Gauge study results show outstanding repeatability and reproducibility across 3 operators measuring each location 10 times. In plot above, all 30 measurements for each location are overlayed. Highest standard deviation for any location was 1%. Nominal values for standard were 32, 63, 125, 250, 500, & 1000 micro-inches. All of these measurements, with three operators, took a total of ~15 minutes.

5. SUMMARY

Hand-held, 3D shop floor gauges for determination of shot peened surfaces provide numerous benefits for the production of precision machined components. Alignment of the instrument to the part is no longer critical to getting the correct results. Increased amounts of data and measurements over a large field of view allow variations within a part to be readily examined. The large amount of data available, typically millions of points, allows for excellent repeatability and accuracy, allowing inspectors to readily determine if parts need rework, should be failed, or pass specifications.

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