3D shop floor characterization of radii and chamfers

Erik Novak, Kramer Lindell, Jared Wheeler
4D Technology, 3280 E. Hemisphere Loop, Tucson, AZ 85706, USA

ABSTRACT

The sharp edges of most precision machined surface must be 'broken', which involves rounding them or adding a flat chamfer. Part longevity, human safety during handling, and proper performance of the component is the intended application of this edge breaking. Traditional visual inspection or single-trace metrology is insufficient to assure parts are within specifications. This paper will present a handheld, 3D-measurement device using polarized structured light which allows for rapid, simple, shop-floor measurement of edge break, chamfer angles, and other precision part geometries. 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, edge break, chamfer, radius measurements

1. INTRODUCTION

Optical metrology based on interferometry, fringe projection or speckle methods[1] has become indispensable to quantify 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-measurement systems of key geometries save time and improve accuracy. Parts do not have to be moved to a measurement laboratory for characterization, and 3D characterization eliminates the errors associated with misalignment of a 2D trace against a radius or edge. 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.

Key parameters called out on almost all design drawings of machined parts are edge break or chamfer geometries. Whenever a sharp corner is machined, the edge is typically 'broken' by rounding it off or by machining a flat to reduce the sharpness of the edge transition. Performing this operation serves different purposes depending on the application. First, sharp edges can pose a safety risk to those coming into contact with the parts; a major truck engine manufacturer found that injuries from sharp machined edges was their number one source of on-the-job injuries and instituted strict edge break controls on all parts. For other parts subject to high stresses, radiused and chamfered edges are necessary to limit possible fracture points along the edge when under high loads. Yet other components, such as turbine blades in a jet engine, need very precise edge break geometries to ensure proper function, as the edges have a large effect on air flow. Finally, chamfer geometries are precisely controlled when using fasteners such as screws and rivets to ensure the fastener does not protrude from the rest of the part. In all cases, knowing the geometries is important to proper performance of the machined part.

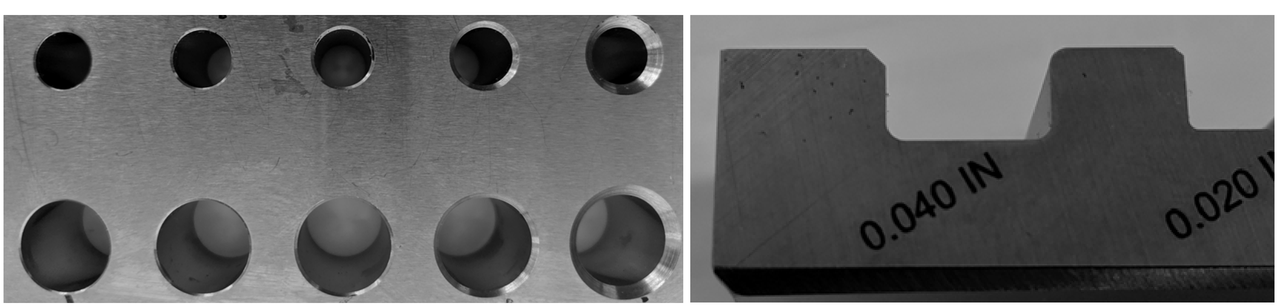

Figure 1. Various chamfered holes used as a reference for visual comparison (left). A machined standard (right) with both flat chamfered edges and rounded edges.

2. CURRENT MEASUREMENT METHODS OF STRUCTURES ON MACHINED SURFACES

Assessing the geometries on machined parts on the production floor commonly relies on visual or stylus-based methods. Visual methods are very subjective, with results depending on the operator, lighting and alignment of the visual comparator, and they provide no quantified documented data. While these informal methods are easy and convenient, they are often insufficient for gauge-capable results with current tolerances. More quantitative measurement can be achieved via replication of the edge using a rubber material, cross-sectioning of the edge perpendicular to the radius or chamfer, and use of an optical comparator or shadowgraph. This procedure is very time consuming and only produces accurate results if the cross-section is perfectly perpendicular; otherwise the chamfer or radius will measure artificially large.

Laser-based gage guns can provide some shop-floor capability for edge break and chamfer measurements, but again only over a single line. Thus, alignment errors persist, and variations in the geometry across the edge are not assessed but rather only a single line is measured. They also typically have lateral and vertical resolutions of tens of micrometers and cannot measure fine geometries. Material finish, reflectivity and slope also affect the measurement using laser-based gauges. The final instrument-based method for assessing edge break and chamfer geometries is use of a portable 2D stylus profiler[4], which may in some cases be placed on the object. This system again suffers from alignment errors, is easily affected by vibration, and often cannot measure over sharp edges without breaking the stylus tip. In addition, stylus profilers for shop-floor use have small vertical range and often cannot measure large chamfers on machined holes. Due to setup time and scan time, it can take more than 30 minutes to achieve a single high-quality trace.

Fringe projection systems can provide the needed precision and portability required for shop-floor characterization of edge break and chamfer geometries. 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. 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 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]

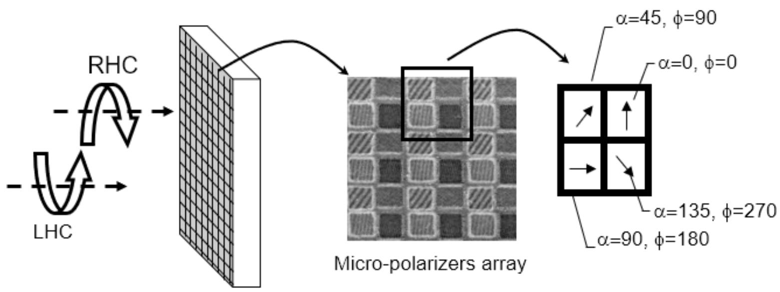

Figure 2. Instantaneous phase shifting method for two orthogonally-polarized wavefronts (Right-Hand Circular and Left-Hand Circular) by a camera with micro-polarizer mask with polarizers oriented at angles 0, 45, 90 and 135 degrees and introducing 0, 90, 180 and 270 degrees phase shift between beams.

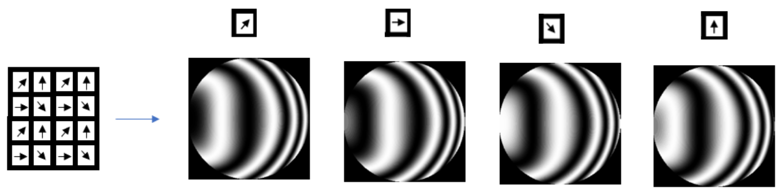

Figure 3. Fringes extracted for polarizers of the same angular orientation.

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.

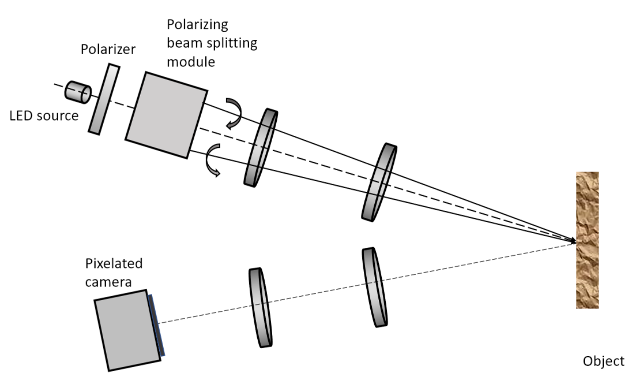

Figure 4. Schematic diagram of single frame polarized structured light system.

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. EDGE BREAK AND CHAMFER MEASUREMENTS

Calculating edge break and chamfer geometries accurately requires both a highly capable measurement system as well as extensive data processing techniques to adequately section the data and perform all of the required calculations. In a two-dimensional measurement system, a line is fit to each of the two sides of the corner. The radiused or chamfered portion of the trace is determined by looking at when the best-fit lines deviate by some set amount from the surface trace. For an edge break radius calculation, a best-fit circle is then fit to the trace that resides between the two end points of the lines. For a chamfer calculation, the linear distance between those end points is calculated. In addition, other parameters are typically calculated, such as the length of the extensions of each side to where they intersect, the angle between the two sides of the trace, and others. Key geometries for edge break and chamfer quantification are outlined in Figure 5 below.

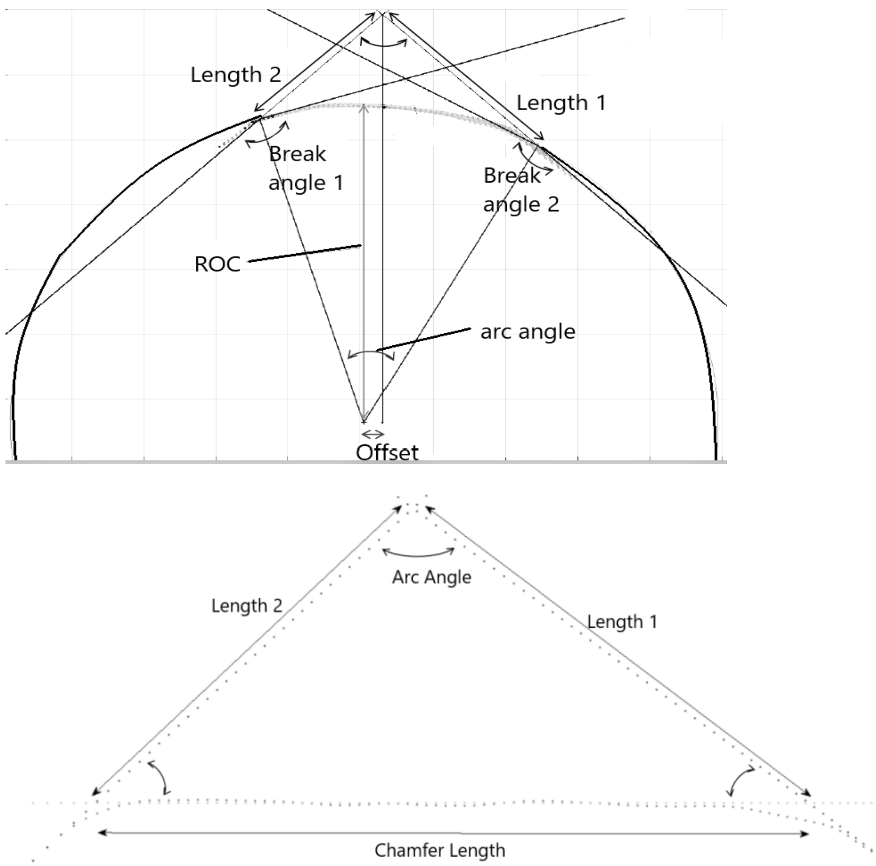

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Figure 5. Key geometries of edge break radius (top) and chamfer (bottom) which require calculation using 2D data

Typical tolerances on lengths for precision machined parts are around 150 micrometers and on radius are on the order of 300 micrometers. For gauge-capable results, in which errors due to reproducibility and repeatability of the measurements are considered negligible, you typically will need a measurement system to have resolution at least 10 times better than the tolerances. Thus, polarized structured light, which can exhibit vertical resolution better than 2 micrometers over a 2.5mm vertical range, provides a good solution.

Using single traces to calculate edge break and chamfer geometries has many limitations. The first one is the need to precisely align the trace perpendicular to the edge. If you do not, you will measure an artificially large radius. This is readily illustrated below using various traces across a 3D part measurement. The radius increases as the traces are less perpendicular to the axis. Also, it is worth noting that while the operator here attempted to align the corner with the instrument, there is still a slight skew to the data. Thus, using a strict trace along the X axis would give an incorrect result. Below the error is a few percent even for the 3 center traces, which may mean the difference between a part functioning properly and failing during use. A similar error occurs with lengths, as the distance along a chamfer will be longer due to cosine errors as you measure non-perpendicular to the edge.

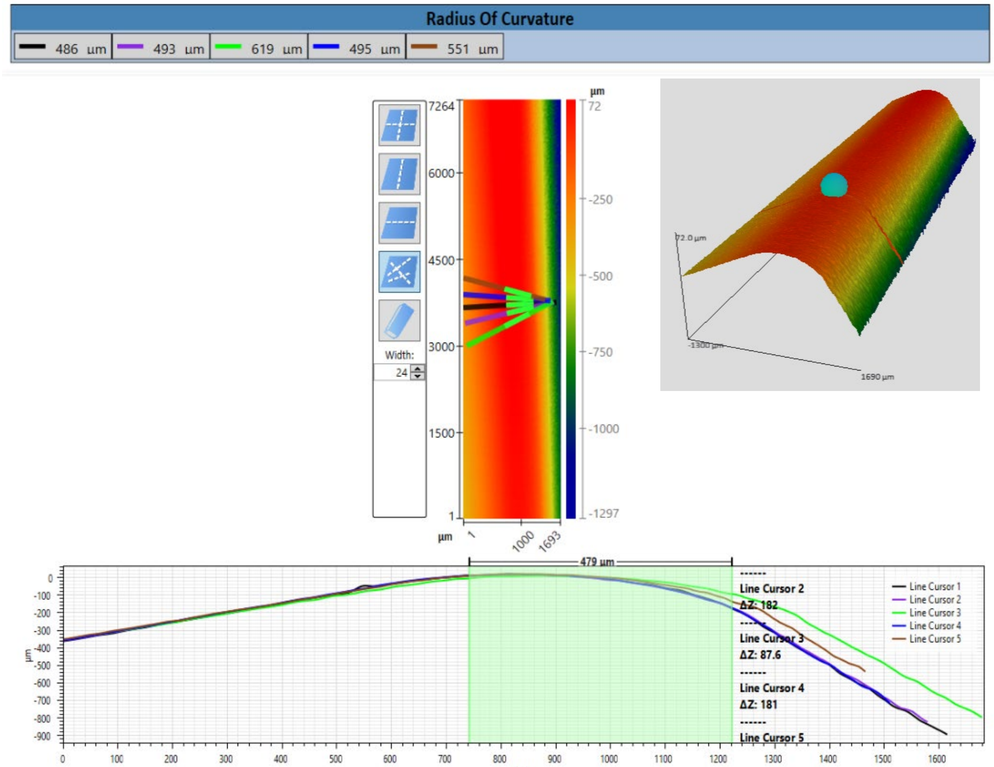

Figure 7. A measurement of edge break radius and calculation of the radius along various 2D traces. The radius increases for nay trace not perfectly perpendicular to the edge.

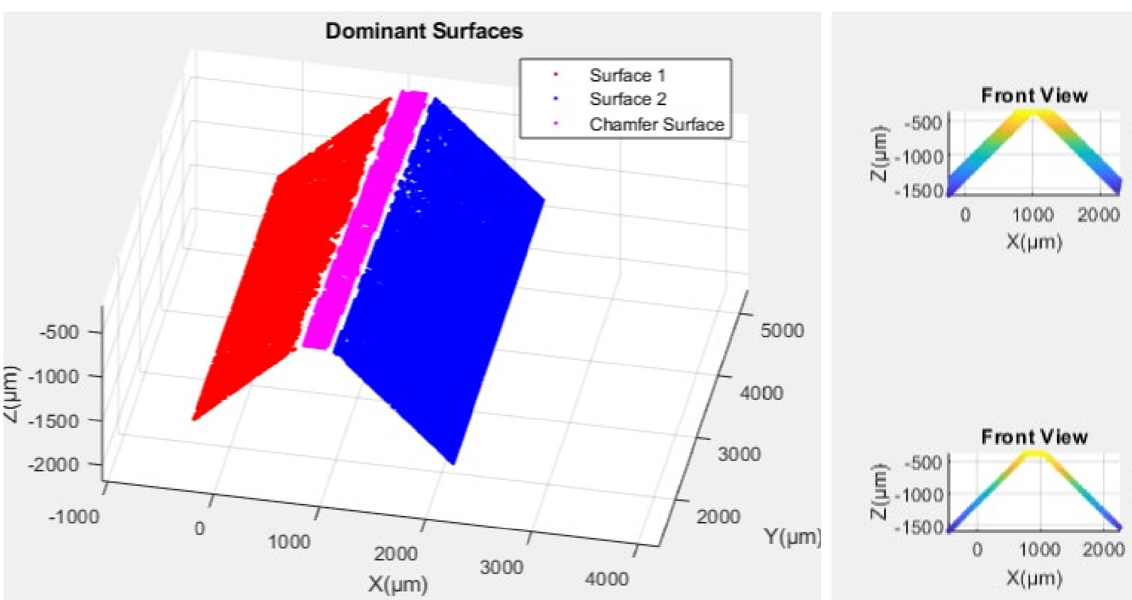

Figure 8. A 3D Chamfer measurement (left) showing the two side planes and chamfer areas. On the right, the projection of the geometry in the X axis before (top) and after (bottom) alignment using the 3D information.

Using 3D data, one can precisely find the key geometries via plane and cylinder fits, rather than simple line and circle fits. Then, since 3D instruments such as the PSL system described in this paper take millions of data points, any noisy points can be readily eliminated, ensuring even higher confidence in the end result. The overall geometry may then be well-understood, and the data realigned such that all calculations are exactly perpendicular to the edge. Figure 8 above shows the parsed 3 planes used in the chamfer calculations (left) and then in the upper right shows a projection of the original measurement along the X axis, where the thickness of the geometry shows that the parts was not precisely aligned. The lower plot shows the aligned-data, where all the traces across the measurement now fall on top of one another. Thus, any calculations along the measurement will be consistent.

The other major issue with two-dimensional results is the overall limited data they provide on the process. With a single trace, one cannot know how much the geometry varies along a part. Typically, there are only a few thousand data points, taken from a single point along the edge. However, PSL measurements contain nearly 4 million points and can measure over 15mm along an edge in a single snapshot. This allows calculation of peak-to-valley, average, and standard deviation of the results so that the operator can pass or fail parts with confidence. An example of how large amounts of data can be useful is illustrated below in figure 9. In the left example, the radius along the measured area of the part is very consistent, only varying slightly with changes in machining. In the right another component shows more than a 20% variation in radius across the 8mm measurement field of view. Thus, parts can be disposed based on both their average values as well as their deviations.

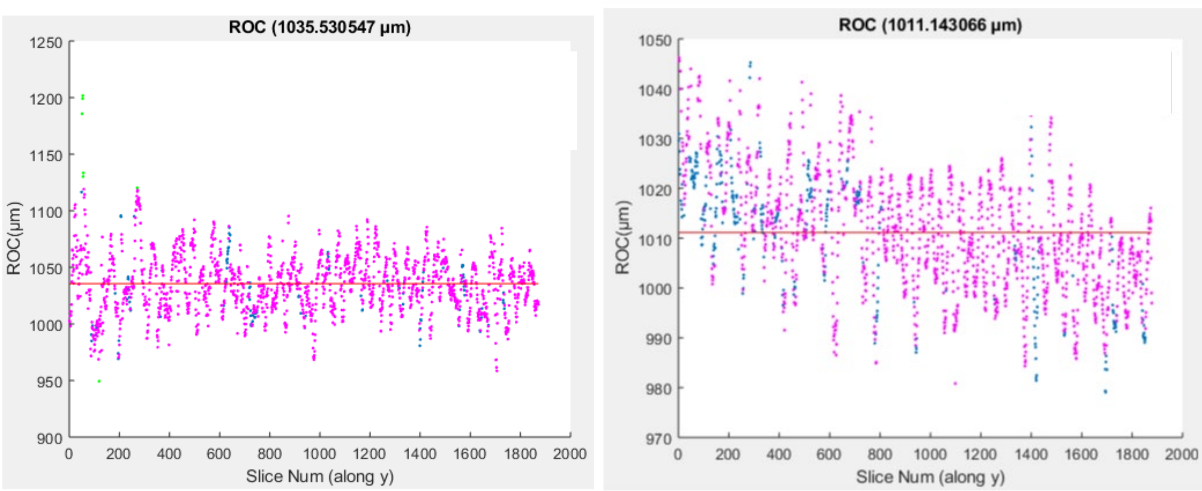

Figure 9. Consistent radius results from a machined part (left) and highly variable results (right) along two different machined corners.

Figure 10 below shows a graph of calculated chamfer and edge break radius results versus the measured values from the manufacturer on a machined stainless component. The manufacturer measured these pieces using an optical comparator and stated results below 0.02" (508µm) were difficult for them to assess. For the chamfer results, the data agree almost perfectly, with a slope of 1, and R^2 of 1 and an offset of just 0.0003" (7 µm). However, each optical comparator result took more than 15 minutes to achieve whereas all PSL results together were taken in under a total of 15 minutes and could be faster using automation. The radius results didn't agree as well, mostly due to the small radii that the optical comparator struggled to measure, but the R^2 was nearly 1, slope of 0.98, and 10 µm. Repeatability for any given result was better than 2.4 µin (60nm) and better than 0.1% of the target value. Thus, the 3D results are both accurate and repeatable over a wide range of geometries. For production lines, such reduced uncertainty generally leads to an increase in yield, since in many applications inspectors will reject parts rather than risk a bad part going further in the production process.

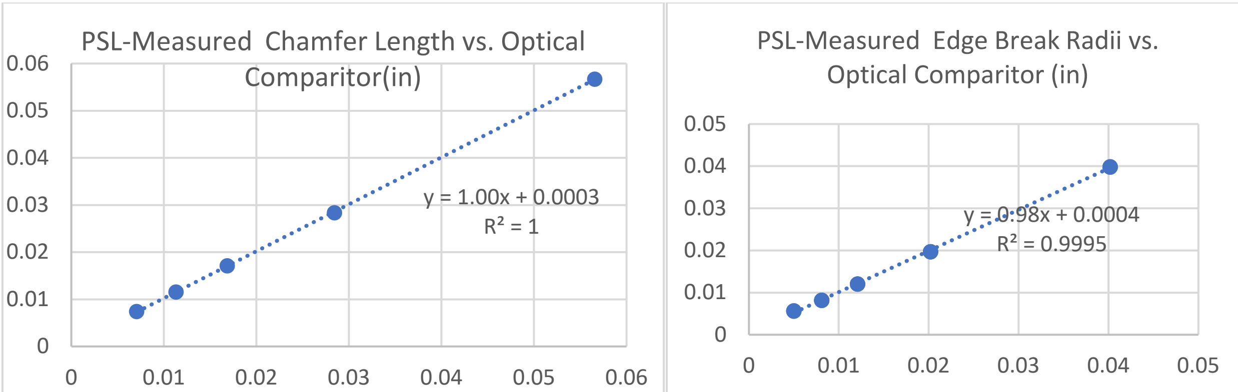

Figure 10. Calculated chamfer and edge break radius results versus the measured values from the manufacturer on a machined stainless component.

5. SUMMARY

Hand-held, 3D shop floor gauges for determination of critical geometries 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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