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A Comparison of Surface Roughness Measurement Methods for Gear Tooth Working Surfaces

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Abstract

Surface roughness is a critical parameter for gears operating under a variety of conditions. It directly influences friction and contact temperature, and therefore has an impact on various failure modes such as macropitting, micropitting and scuffing. Typically, gear tooth surface roughness is measured using a stylus profilometer, which yields a two dimensional cross section of the surface from which roughness parameters are taken.

Stylus profilometry can produce inconsistent results if measurements are not executed correctly. Variables such as measurement parameters, stylus tip radius, and repeatability of stylus orientation relative to the gear tooth can all impact measurement results. This paper examines measurements from one “shop floor” and one “metrology lab” profilometer, both using two different stylus tip radii on the same gear teeth. Measurements from ground, shot peened and superfinished surfaces are compared.

Although stylus profilometry is convenient, a limited amount of information regarding the surface topography of the tooth is retained. Tooth replicas subsequently evaluated with optical interferometry offer an alternative means to measure surface roughness, and allow for retention of a much more complete representation of the tooth surface for future evaluation. The three dimensional surface profile generated by optical interferometry can also highlight features that would be difficult to evaluate using stylus profilometry. This paper compares roughness measurements made using optical interferometry of gear teeth with optical interferometry of tooth replicas. Two different replication techniques are evaluated. The same teeth measured using stylus profilometry are used, thus the interferometry results are directly compared to the profilometry measurements. Lastly, when tooth replicas are taken and measured with optical interferometry, the reference frame of the gear from which the replica is taken is not immediately apparent. A method for correlating tooth replica coordinates to roll angle is also presented, which is shown to be useful for plotting roughness trends at points of interest over the active profile of the tooth.

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1 Introduction

Surface roughness is a critical parameter for gears operating under a variety of conditions. It directly influences friction and contact temperature, and therefore has an impact on various failure modes such as macropitting, micropitting, scuffing and wear. Since surface topography is critical to gear performance, evaluation of roughness parameters using established measurement practices according to current standards is essential. Even within the framework of the established standards, a number of measurement methods are possible. This work aims to compare measurement results from various measurement techniques to examine the reproducibility of results when measuring the same spur gear teeth across multiple methods.

Surface roughness measurement generally falls into two categories, contact and non-contact. The most common method of measuring the surface roughness of gear teeth is with a contact stylus profilometer, which typically uses a conical stylus with a spherical tip made from diamond. [1] A disadvantage of stylus profilometers is that they only measure the topography of two dimensional cross sections of a three dimensional surface. For this reason, if the surface has localized features that are significant to the roughness measurement, it is quite possible that the stylus may not traverse across them. Also, some topography features that can provide valuable information about the surface are not as intuitively obvious when only evaluating two dimensional cross sections. Despite these limitations, stylus profilometers are relatively inexpensive, portable and practical for manufacturing environments. For these reasons they are widely used.

There are a number of non-contact roughness measurement methods, including laser triangulation, atomic force microscopy (AFM), confocal microscopy and optical interferometry. [1] This work focuses on optical interferometry, which is practical for generating three dimensional (areal) roughness measurements on gear teeth. One advantage of optical interferometry is that a three dimensional representation of the surface is obtained, which allows for very effective evaluation and visualization of roughness features. Also, since this method scans an area rather than a cross section, a much larger area of the surface being measured is evaluated. This is advantageous for finding features that occur only in localized areas which might not be observed with stylus traces. Optical interferometry is not without its disadvantages however, one significant drawback is that interferometry equipment is significantly more expensive than a typical stylus profilometer. Interferometer measurements also generally require more setup and measurement time. Lastly, optical interferometry requires a line of sight from the objective lens to the measurement surface with the requirement that the surface must be nearly perpendicular to the objective. Depending on the instrument available, focal distances may be short, which means that it may not be possible to measure gear teeth without cutting them from the gear.

An alternative to measuring the actual gear teeth is to make replica castings of the tooth space and to subsequently measure the replicas. One advantage of this method is that replicas can be preserved for later evaluation, which can be especially beneficial in research environments. The goal of this work was to evaluate both contact and non-contact roughness measurement techniques, as well as two different replica casting materials.

2 Related Work

A large body of work exists on the topic of metrology and surface texture measurement. General guide books [1] [2] are available that provide descriptions of surface texture parameters as well basic overviews of various measurement technologies. Methodology is discussed in [3] that is more specific to measurement of gear tooth surfaces with stylus instruments, and technology by which surface roughness can be measured in-process on gear inspection equipment is discussed in [4] and [5].

It is well established that roughness measurements can be influenced by incorrectly altering parameters such as evaluation length and filtering. For this reason, standards pertaining to roughness measurement parameters exist and should be used as the basis for any measurement process. ISO-4287 [6], 4288 [7] and 3274 [8] are the standards that form the basis for all of the measurements taken in this work. These standards define the roughness parameters, procedures for measurement, and the requirements of contact stylus instruments used in the measurement of surface roughness. ISO 25187-2 [9] also provides the basis for three dimensional areal roughness parameters. Although the standards are quite detailed, the key points they offer are straightforward. A concise summary of all three standards and how they relate to measurement of gear tooth working surfaces is presented in [10] and [11], and summaries of profile filtering are available in [12] and [13].

The subject of variation in roughness measurement was studied by Wieczorowski [14], where several research centers and industrial labs made stylus measurements on the same samples. The conclusion reached was that even when using the same roughness parameters and samples, measurements made by different operators using different instruments could result in a high degree of variability. This further reinforces the fact that roughness measurements must be made carefully with methods prescribed by established standards.

Liu et. al. [15] discuss the accuracy of various surface replication techniques tested on flat roughness standards, as well as the advantages and disadvantages of the replication compounds tested. Jolivet et. al. [16] conduct a similar study on flat roughness test coupons where the authors find that the selection of the ideal replication compound is dependent on the roughness range of the sample being measured. Peng [17] discusses scanning an entire gear using non-contact optical methods, however this work was focused on inspection of macro surface features such as lead and profile measurements. Creating replicas and measuring the surface roughness of gear teeth can present unique challenges not present in flat coupon testing, which was the motivation for this effort. In total, over 400 roughness measurements were taken to compose the data sets presented.

3 Experimental Overview

3.1 Test Gears

The three spur gears selected for this study were all of the same module, tooth count and face width, and were chosen to represent a variety of surface finishes typical of aerospace gearing. A summary of the relevant gear data is shown in Table 1. Four previously untested flanks from each gear were selected for roughness evaluation.

Table 1 – Gear data

	Gear #1	**Gear #2**	**Gear #3**
Surface Condition	As-ground	As-ground + shot peened	REM Isotropic Superfinished (ISF®)
Pressure Angle (deg)	20	25	20
Gear Type	Spur		
# teeth	28		
Module (mm)	3.175		
Face Width (mm)	6.35		
Material	AISI 9310		

ISF® is a registered trademark of REM Surface Engineering

3.2 Tooth Replicas

Before stylus measurements began, replicas of all teeth identified for evaluation were made from both compounds shown in Table 2. One advantage of the silicon rubber compound is that is easily releases from the tooth after curing due to its pliable nature, where the hard epoxy requires chilling the gear with compressed CO_2 in order to remove the replica from the tooth space. The hard epoxy on the other hand can be traced with a stylus profilometer, where the silicon rubber cannot. The goal of this exercise was to evaluate the effectiveness of each compound in replicating a range of surface conditions, as well as to establish which is more practical from a usability and handling perspective.

Table 2 - Replication compound data

	Silicon Rubber	**Hard Epoxy**
Manufacturer	Struers	Flexbar
Type	RepliSet –F5	Facsimile
Detail Reproduction (per data sheet)	Down to 0.1 µm	0.003 to 50 µm
Hardness	30 Shore A	90 Rockwell M (Comparable to ABS plastic)

3.3 Silicon Rubber Replication

Figure 1 shows an outline of the following silicon rubber replication process:

1. Clean the tooth space to be replicated with parts cleaning solvent, followed by an isopropyl alcohol rinse, then immersion in an ultrasonic parts cleaner with isopropyl alcohol for 30 minutes;
2. Dam the sides of the tooth space;
3. Apply the two part mixture; using the supplied syringe (components are mixed during application in the syringe tip)
4. While the mixture is still uncured, apply a strip of backing paper;
5. Allow to cure for 30 minutes, remove from the tooth space;
6. Protect replicas from damage in hard plastic containers.

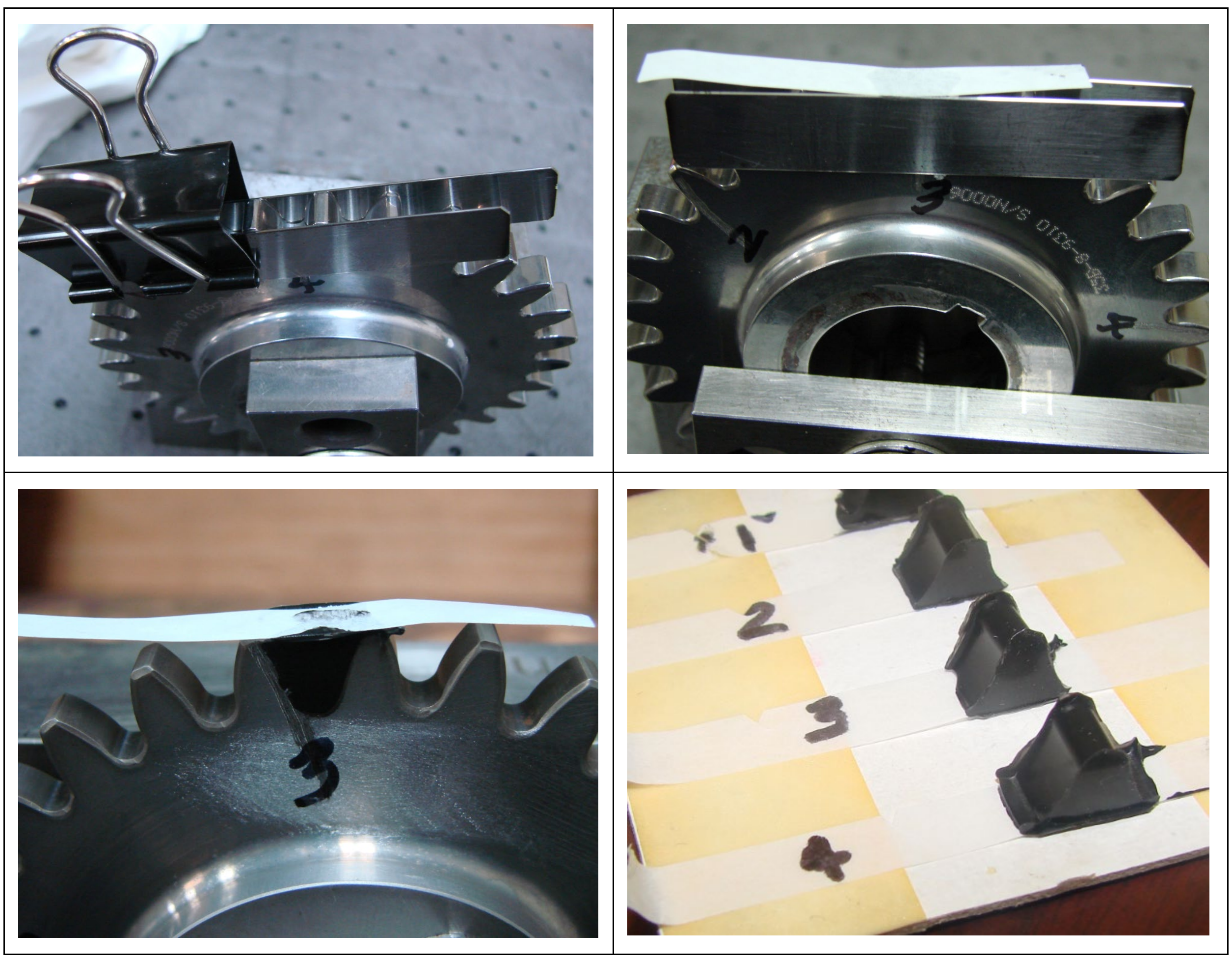


Figure 1 - Silicon rubber replication process

3.4 Hard Epoxy Replication

Figure 2 shows an outline of the hard epoxy replication process:

1. Clean the tooth space to be replicated;
2. Dam the sides of the tooth space;
3. Mix the two casting components in a 3:1 ratio for 30-45 seconds so no clumps of powder remain;
4. Draw the mixed epoxy into a syringe with an appropriate sized tip, the act of drawing into the syringe helps to de-gas the mixture and prevents voids in the casting;
5. Quickly apply the epoxy to the tooth space (pot life is roughly 3 minutes);
6. Before the epoxy cures place the label / tag into a non-critical area;
7. Allow to cure for at least 30 minutes;
8. In order to release the replica from the tooth space, rapidly chill the gear in the vicinity of the replica (compressed CO_2 was used).

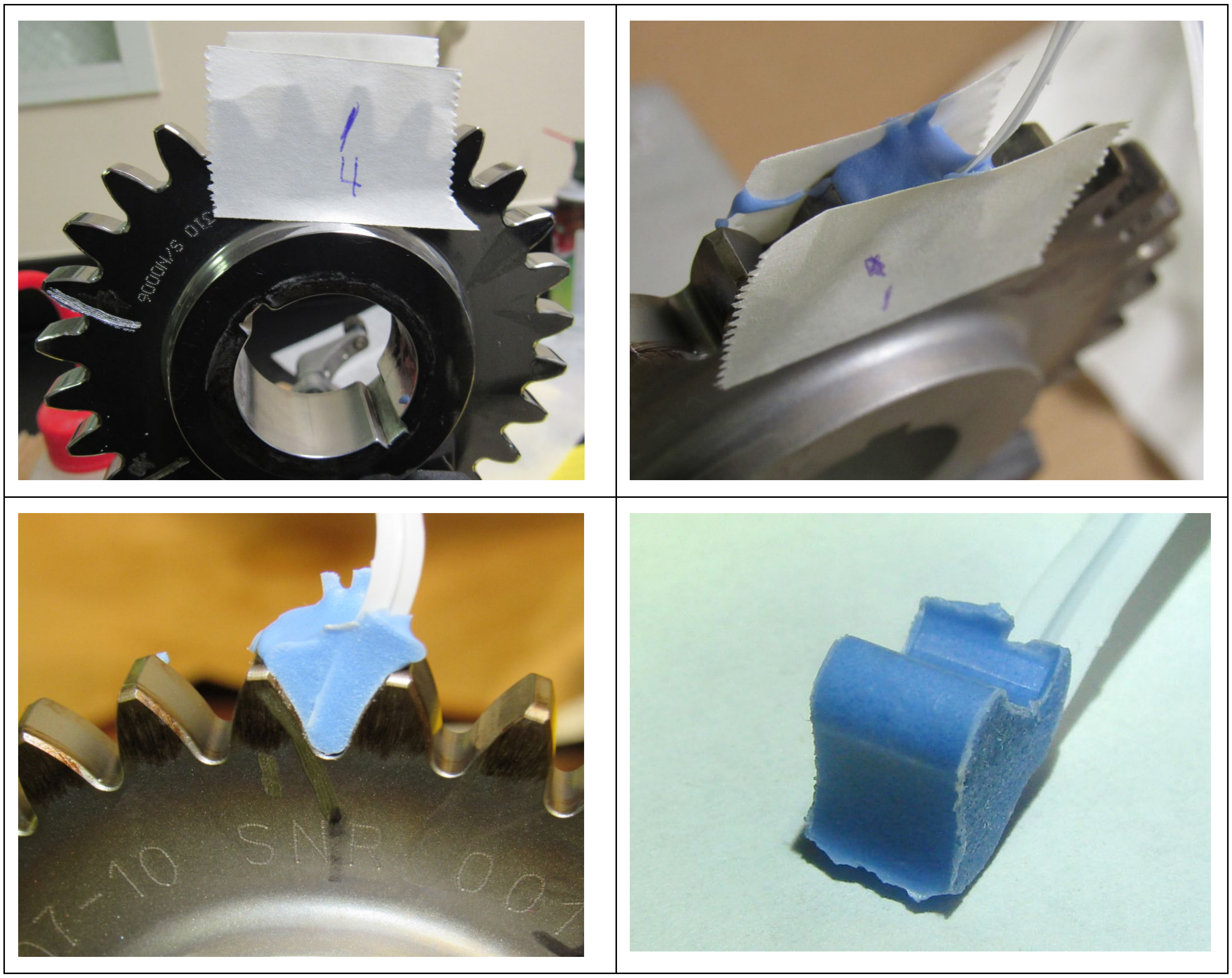


Figure 2 - Hard epoxy replication process

3.5 Stylus Profilometers

The two different profilometers shown in Figure 3 and Figure 4 were used for the stylus measurements forming the baseline data set. Profilometer A is a “shop floor” model with a portable measurement head that can be mounted with various types of fixturing. Profilometer B is more typical of a unit found in a metrology lab, in that it is not as portable and has X/Z stage for positioning of the stylus tip. Both models maintain static positioning of the gear and measurement head during a trace (unlike some gear inspection machine based solutions [5] that rotate the gear during measurement). The relative angle of the stylus tip and working surface are monitored to be within defined limits in software. Calibration was carried on a nominal glass calibration patch (Ra = 0.28µm) for both profilometers with both stylus tips, and all were found to be within expected limits. A summary of the measurement resolution capabilities of each instrument is shown in Table 3.

Figure 3 - Profilometer A, "shop floor" model

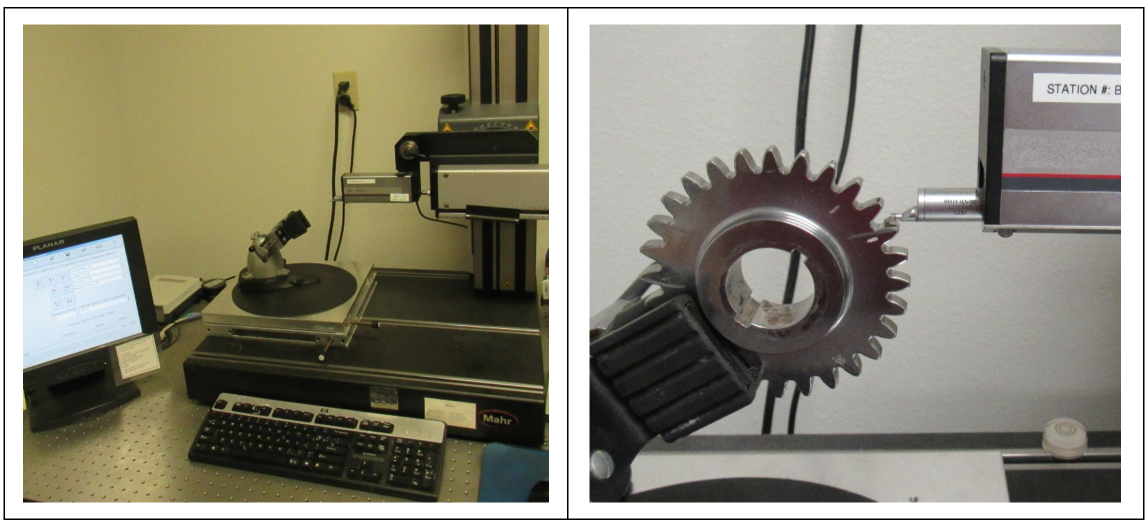


Figure 4 - Profilometer B, "metrology lab" model

Table 3 - Profilometer resolution

Profilometer	Measurement Condition	Lateral Resolution (µm)	Vertical Resolution (µm)
A	As-ground As-ground + peened	0.5	0.01
A	ISF	0.16	0.01
B	As-ground As-ground + peened	0.5	0.001
B	ISF	0.5	0.001

3.6 Stylus Tips

The stylus tip radius can easily be an overlooked parameter in the setup of surface roughness measurements. It is desired to select a stylus that has the ability to trace the surface features of interest with minimal mechanical attenuation due to the radius of the tip. ISO 3274 and 4288 together define roughness parameter ranges and recommended stylus tip sizes within those ranges as shown in Table 4.

According to ISO, a 2µm tip should be used for all measurements in this work, with the as-ground and as-ground / peened surfaces being near the Rz exception where a 5µm tip might be usable. For both profilometers selected, 2µm and 5µm nominal stylus tips were available for use, so both were tested to evaluate the impact on measurement results. The stylus tip radii were measured when received from the manufacturer and determined to be 2.97µm and 4.7µm respectively. Nominal tip radius values are reported in all figures and tables.

Table 4 - Recommended stylus tip radii per ISO 3274 and 4288, (for non-periodic profiles)

Ra range (µm)	Rz range (µm)	Tip radius (µm) per ISO 3274
0.02 < Ra ≤ 0.1	0.1 < Rz ≤ 0.5	2
0.1 < Ra ≤ 2	0.5 < Rz ≤ 10	2*
*For Ra > 0.5 µm or Rz > 3 µm, a 5µm tip can usually be used without significant differences in measurement results		

3.7 Interferometer

An optical interferometer with a 570nm white light source was used for all non-contact measurements. The objective lenses shown in Table 5 were available, with the 10x chosen as a starting point since it had been used most often in previous work. Two-sided adhesive was used as a simple but effective means to fixture the gear teeth and replicas during measurement as shown in Figure 5.

Table 5 - Optical interferometer objective lens specifications

Objective Lens	Scan window size (mm)	Optical Resolution (µm)	Spatial Sampling (µm)	Vertical Resolution, CSI[1](µm)	Vertical Resolution, 3XCSI[2] (µm)	Approximate Scan Time[3] (minutes)
2.75x	3.0	3.56	2.93	0.003	0.011	2
10x	0.83	0.95	0.81	0.003	0.011	3
20x	0.42	0.71	0.41	0.003	0.011	5
[1]CSI – Coherence Scanning Interferometry measurement mode [2]3XCSI – Uses 3X scan rate for higher throughput with decrease in vertical resolution [3]Approximate scan time to acquire 3.3mm long scan using 3XCSI measurement mode						

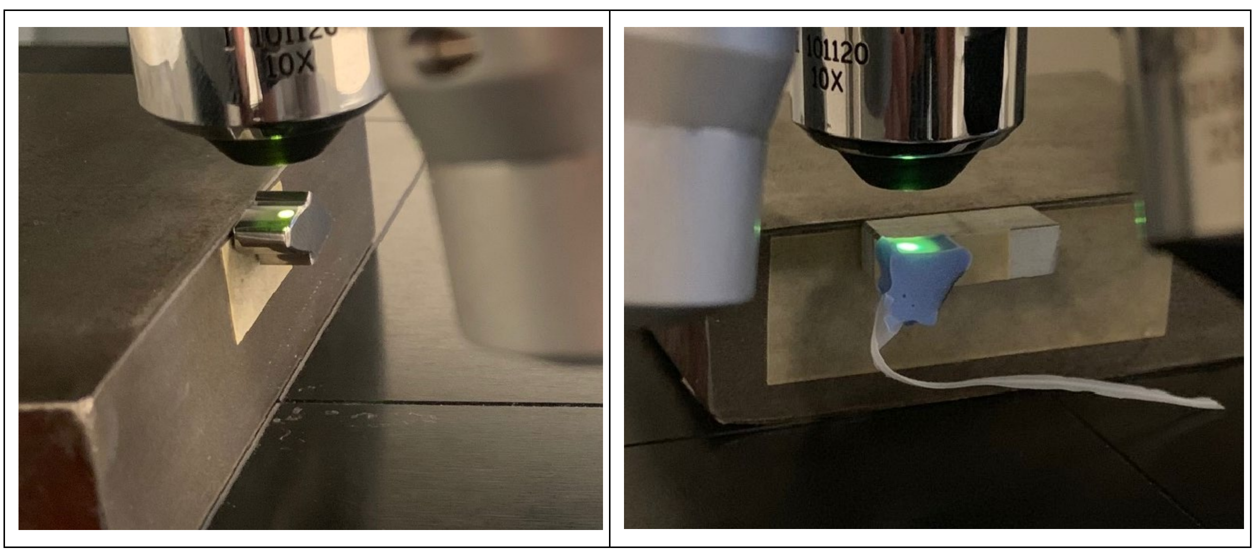


Figure 5 - Gear tooth and hard epoxy replica in interferometer

4 Surface Roughness Measurements

4.1 Profilometer Measurements

Profilometer measurements were carried out on of four teeth from each specimen gear, using profilometers A and B with both 2μm and 5μm stylus tip radii. Measurements were taken centered approximately on the pitch line, with four measurements per tooth taken at 20%, 40%, 60% and 80% across the face width. The filtering and measurement parameters used are shown in Table 6 and were based on the guidelines established in ISO 3274 and 4288.

Table 6 - Profilometer measurement parameters

Surface Condition	Profilometer	Traverse Length (mm)	Evaluation Length (mm)	Lower Cutoff λc (mm)	Upper Cutoff λs (μm)	Filter Type
As-ground, As-ground + shot peened	A	4.8	4.0	0.8	2.5	Gaussian (phase correct)
	B	4.0	2.4	0.8	2.5	
ISF	A	1.5	1.25	0.25	2.5	
	B	1.75	1.25	0.25	2.5	

It is worth noting that the only parameter in Table 6 that does not explicitly conform to the ISO standards is the 2.4mm evaluation length of Profilometer B in the as-ground and as-ground / shot peened measurement conditions. ISO recommends an evaluation length of 5 times the lower cutoff wavelength, which yields a recommended evaluation length of 4.0mm for these surface conditions.

Profilometers typically make the traverse length (the total distance traveled by the stylus) slightly longer than the evaluation length (the length across which the roughness parameters are measured) to negate any edge effects during the beginning and end of the measurement. In this case, Profilometer A adds a half of a cutoff length to each end of the evaluation length to arrive at the traverse length. This resulted in a 4.8mm traverse length, which was slightly shorter than the ~5mm tooth flank length available for measurement, which was acceptable. Profilometer B on the other hand adds a full cutoff length to each end of the evaluation length, resulting in a traverse length of 5.6mm per ISO, exceeding the available tooth flank length. Also, Profilometer B's stylus was farther away from the edge of the probe, making it more prone to falling off of the tooth tip at the end of the trace. For these reasons, an evaluation length of 3 times the cutoff was chosen for Profilometer B. This situation is not uncommon on smaller gears with fine teeth, and does not present a problem if the roughness being measured is uniform along the tooth.

4.2 Interferometer Measurements

The optical interferometer was then used to measure replicas of the same teeth measured with the stylus instruments. The specimen teeth were then sectioned from their parent gears and also measured using interferometry. It is not possible to measure gear teeth in the interferometer used in this work without sectioning them from the gear due to space constraints and the close working distance required by the objective lenses.

The first group of measurements were taken using a 10x objective lens (see Table 5), measuring four 0.83mm x 0.83mm windows on the pitch line of each tooth. Coherence Scanning Interferometry (CSI) scanning mode was used with high Z resolution and no averaging. Measurements were taken at 20%, 40%, 60% and 80% across the face width to duplicate the approximate stylus measurement locations. The output of these measurements is a raw data file representing the measured profile of the surface. Further post processing is then required to obtain the desired roughness parameters.

5 Processing Interferometry Data

5.1 Filtering and Evaluation of Three Dimensional Data

The first step in evaluating the three dimensional interferometry data was to invert the data if a tooth replica was measured. This step can be neglected if the parameters being considered equally weight peaks and valleys (such as Ra and Rz), however other parameters such as skewness and bearing ratio will be incorrect if the replica data is not inverted first.

In order to directly compare the results to the stylus profilometry data, the same Gaussian filter and cutoff wavelengths were then applied as summarized in Table 7. After application of filtering to the surface, computation of the three dimensional areal *S*-parameters was carried out as defined in ISO 25178-2.

Table 7 - Interferometry data filtering parameters

	As-ground, As-ground + shot peened	**ISF**
Filter Low Wavelength (mm)	0.8	0.25
Filter High Wavelength (μm)	2.5	2.5
Filter Type	FFT Fixed	
Filter Cutoff	Gaussian	
Filter	Band Pass	
Form Removal	None	

5.2 Two Dimensional Cross Sectioning

In order to more directly compare the interferometry results with the stylus profilometry results, the three dimensional data was then processed further by taking four cross sections across each measured surface to simulate stylus traces. Two dimensional roughness *R*-parameters were then computed for each cross section and averaged as shown in Figure 6. This cross sectioning technique, along with using comparable Gaussian filters on the three dimensional data to compare to stylus measurements is similar to the method outlined by Badami et. al. in [18].

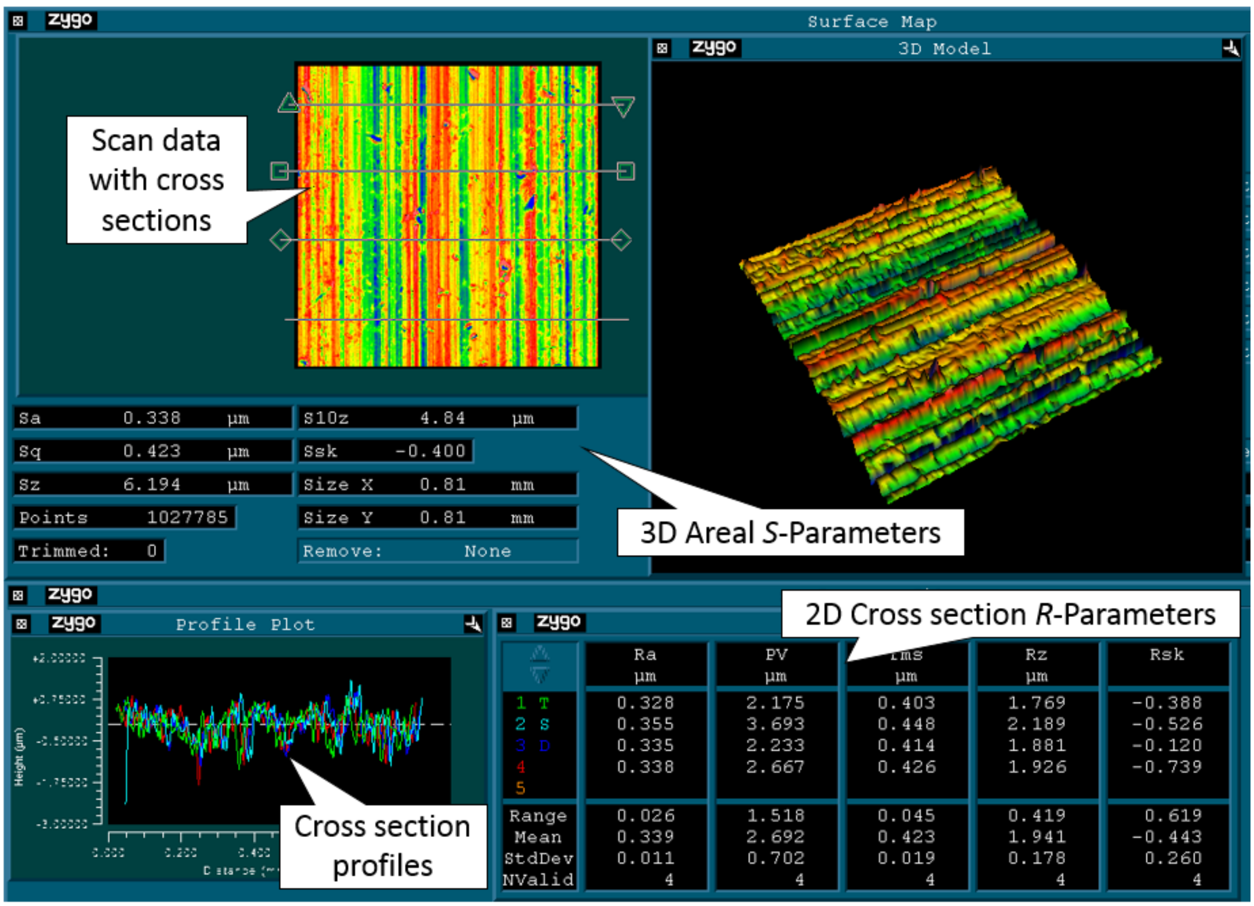


Figure 6 - Processing of interferometry data

6 Comparison of Results

Box and whisker plots were used to compare the data sets. In this type of plot, the solid boxes indicate data which falls between the 25th and 75th percentile of data, and the limits of the error bars indicate the minimum and maximum values in the data set that are not considered outliers. Individual data points outside the error bars exceed the criteria for outliers, in this case a deviation greater than 1.5 times the inner quartile range.

6.1 Profilometer vs. Interferometer Results (2-dimensional profile parameters)

Figure 7 and Figure 8 show a comparison of Ra (arithmetic mean deviation) and Rq (root mean square deviation) from all measurement conditions, comparing the stylus profilometry results with two dimensional roughness *R*-parameters computed from cross sections of the interferometer scans. Several trends are worth noting in these data sets. On as-ground surfaces, the optical measurements were smoother than the stylus measurements of Ra and Rq. This trend was less pronounced on the shot peened and ISF surfaces. Measurement of the gear teeth, silicon rubber and rigid epoxy replicas yielded similar results using optical interferometry, with the exception of the rigid epoxy replica of the ISF surface, which was substantially rougher.

Also, Profilometer A with a 2µm stylus tip yielded the roughest Ra and Rq measurements on as-ground surfaces, which may be due to the longer evaluation length of Profilometer A. As will be discussed further, the roughness along the tooth profile is not always constant, and a longer evaluation length will average in any deviations along the profile.

Figure 9 shows a comparison of Rz (average of maximum peak to valley distances from all sampling lengths in the evaluation length) from all measurement conditions. The decrease in measured roughness when using optical interferometry on the as-ground and shot peened surfaces is more apparent when evaluating this parameter.

The effect of varying stylus tip radius is also shown in this data. Generally, a 2µm tip radius produced rougher Ra and Rq measurements than the same instrument with a 5µm tip, although there are outliers and exceptions to this observation. For this reason, it is important to ensure the stylus tip being used conforms to the specifications set forth in the applicable standards, especially when comparing results across different labs and instruments.

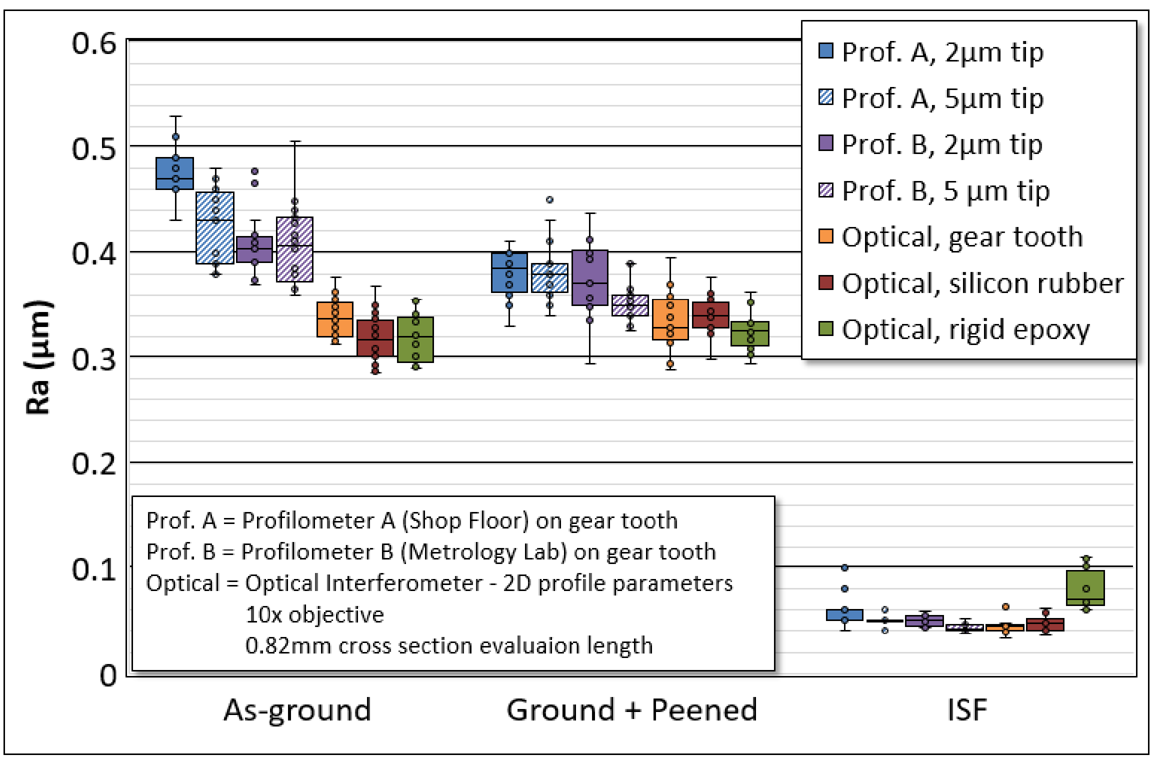


Figure 7 - Ra, profilometer vs. interferometer results

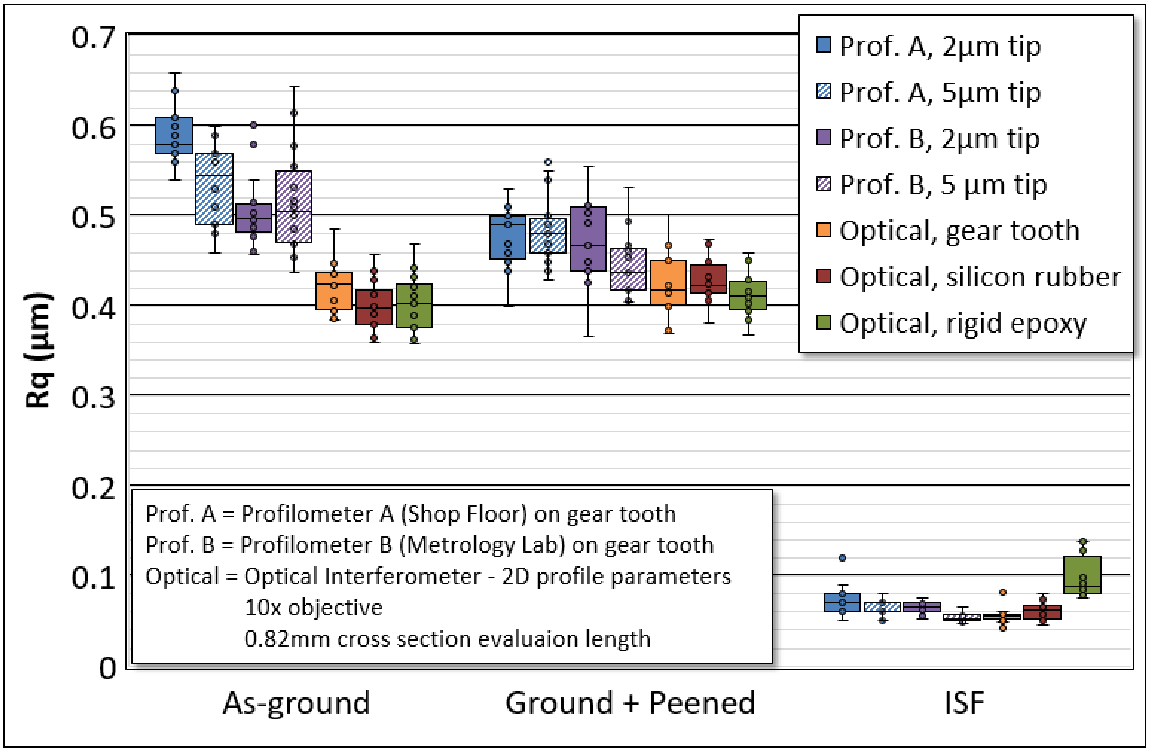


Figure 8 - Rq, profilometer vs. interferometer results

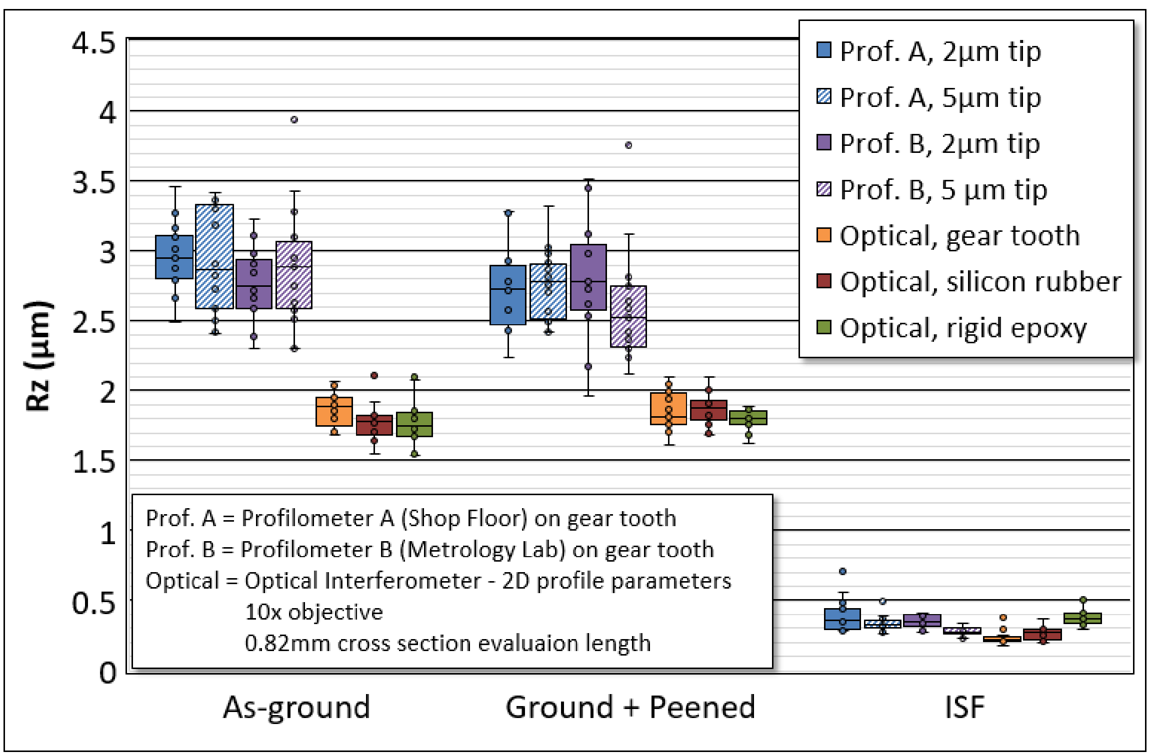


Figure 9 - Rz, profilometer vs. interferometer results

6.2 Interferometer Results (2-dimensional profile parameters vs. 3-dimensional areal parameters)

The *R*-parameters computed from the cross sections of the interferometry data were then plotted against the areal *S*-parameters computed from the three dimensional data taken from the same scan data. A comparison of Ra and Sa is shown in Figure 10. Overall, Ra and Sa were comparable, with Sa yielding slightly rougher measurements in most cases. This is expected, since the computation of Sa takes into account much more data than the cross sections used to compute Ra, which increases the probability of finding outliers.

A comparison of Rz (maximum height of profile in a sampling length) and S10z (average of ten highest peaks to ten lowest valleys over the area) is shown in Figure 11, which shows that S10z yields substantially rougher measurements in all cases. This is also expected, since the probability of finding a high peak and a low valley increases when considering an entire area at once rather than one sampling length in a linear cross section of the data.

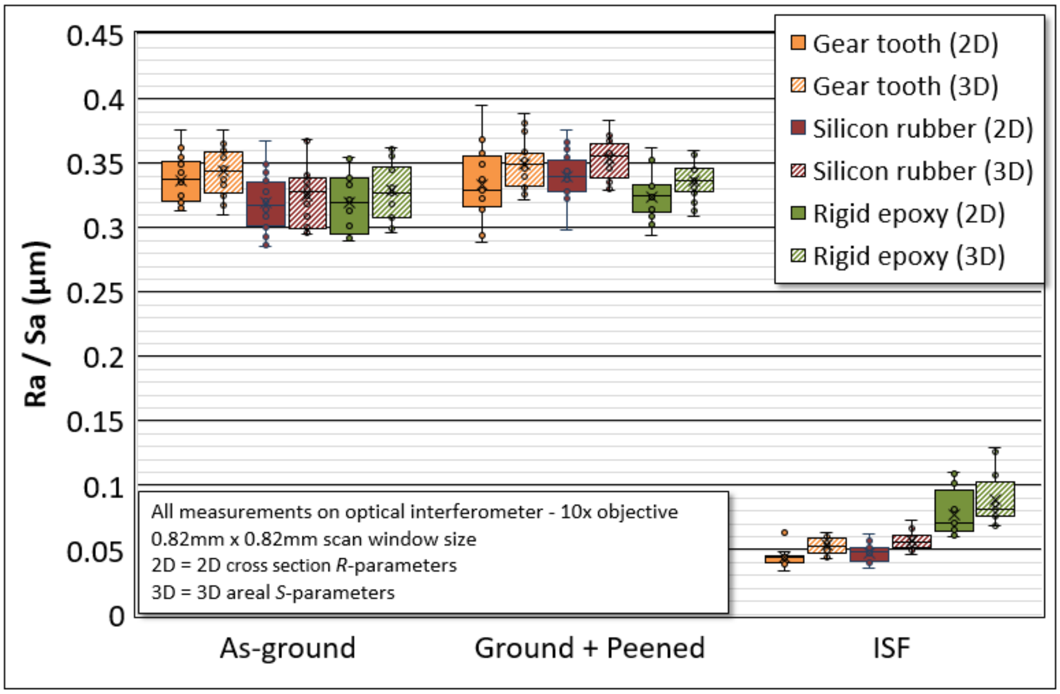


Figure 10 – Ra vs. Sa

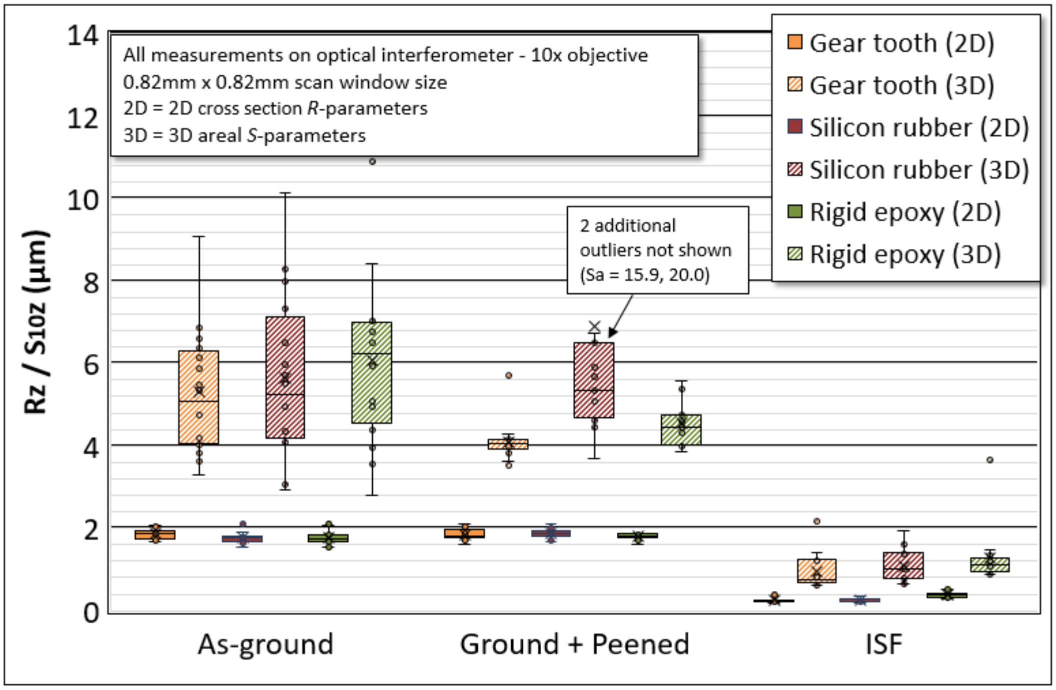


Figure 11 - Rz vs. S10z

7 Further Investigation into Results

Analysis of the data sets presented led to the following questions that warranted further consideration:

1. Why did the optical interferometry data yield lower surface roughness values, which was most notable when evaluating Rz values of the as-ground and as-ground / shot peened surfaces?
2. Can the optical interferometry measurement technique be further refined to produce more representative scans of the surfaces?
3. Why did the hard epoxy replicas of the ISF surface yield rougher measurements than the gear teeth themselves?

In order to investigate these observations, additional interferometry scans were carried out to evaluate the effect of objective lens selection and scan length on roughness results. Also, the hard epoxy replicas were examined in more detail using optical microscopy to gain insight into the characteristics of the replica surfaces. Stylus profilometer readings of the hard epoxy castings were also taken to verify the replication process.

7.1 Variation of Roughness Along the Profile

One potential reason why the interferometry data showed different results than the profilometry data was the small scan size originally used (0.83mm) when compared to the evaluation length of the stylus measurements (4mm). If the roughness of the tooth is not constant over the profile of the tooth, the longer evaluation length of the stylus will take into account and average more of the surface. A technique used previously by the authors is to take an interferometry measurement of the entire tooth profile, then using masks, evaluate roughness in a small window of the profile progressively along the tooth.

In order to provide a frame of reference to the roughness measurements, first an unfiltered cross section is taken from the scan. Equations 1 through 5 (adapted from [19]) are then used to mathematically define an involute curve representing the gear tooth in Cartesian coordinates. The computed involute is aligned to the cross section of the scan data using a series of position and rotation transformations. Final alignment is achieved by using a solver to minimize the error between the two profiles. Figure 12 shows the final alignment of a silicon rubber replica to the mathematically generated involute for that tooth. It is shown that the replica holds the form of the tooth well, with the exception of the tip which has slight deformation due to the pliable nature of the replication compound on the mounting paper.

$$x(r) = r\sin(C_1 - \tan\emptyset + \emptyset) \quad (1)$$

$$y(r) = r\cos(C_1 - \tan\emptyset + \emptyset) \quad (2)$$

$$\emptyset = \cos^{-1}\left(\frac{R_b}{r}\right)\ (radians) \quad (3)$$

$$C_1 = \frac{T_1}{2R_p} + \tan\emptyset_p - \emptyset_p \quad (4)$$

$$\theta = \sqrt{\left(\frac{r}{R_b}\right)^2 - 1} \quad (5)$$

where:

R_b = base radius

r = radius at point along involute curve

R_p = Pitch radius

$\emptyset_p$ = pressure angle at pitch diameter (radians)

T_1 = circular arc tooth thickness at pitch diameter

C_1 = constant defined by tooth geometry

θ = roll angle at point along involute curve

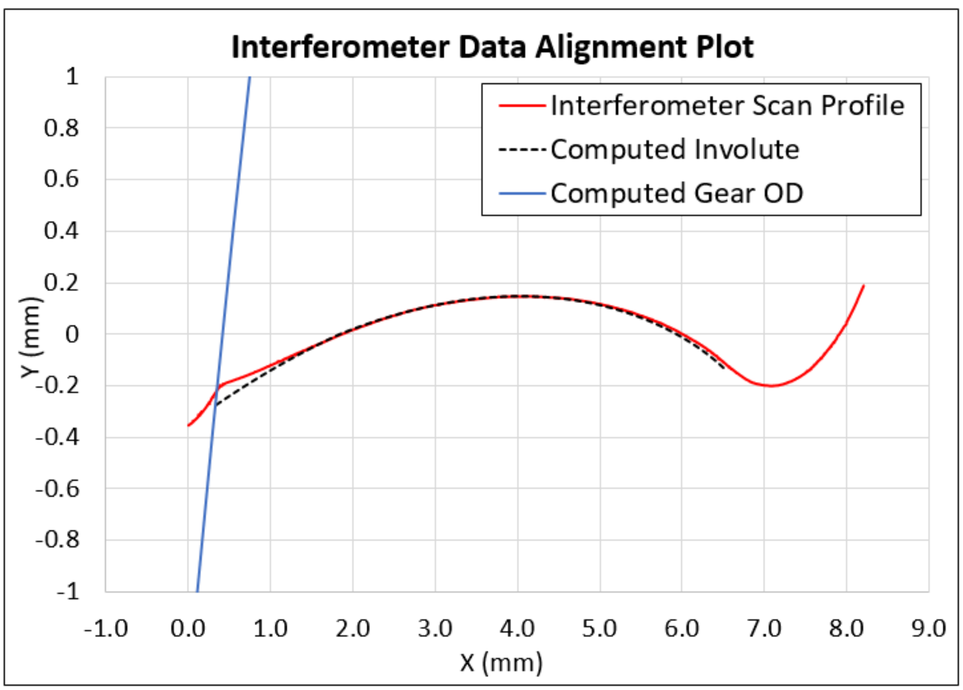


Figure 12 - Aligning scan data of a tooth replica to a mathematically generated involute

Of particular interest to the issue of the interferometer scans differing from the profilometer traces was the consistency of the roughness of the as-ground surfaces along the profile of the tooth. To test this, an interferometry scan of one as-ground tooth was taken, then analyzed with a 0.82mm window incrementally moved along the tooth as described, with the results shown in Figure 13. The scan results are truncated before the end of active profile, just before the edge of the scan window is coincident with the tip of the tooth. It is shown that the roughness along the profile can vary significantly, which provides one potential reason why the stylus measurements differed from the interferometer measurements. If the stylus traverses the majority of the tooth profile, localized variations in roughness will be averaged over the trace. If the interferometry scan window is small, only a portion of the roughness profile will be represented. An ideal interferometry scan would be long enough to fully represent the evaluation length prescribed by the ISO standards.

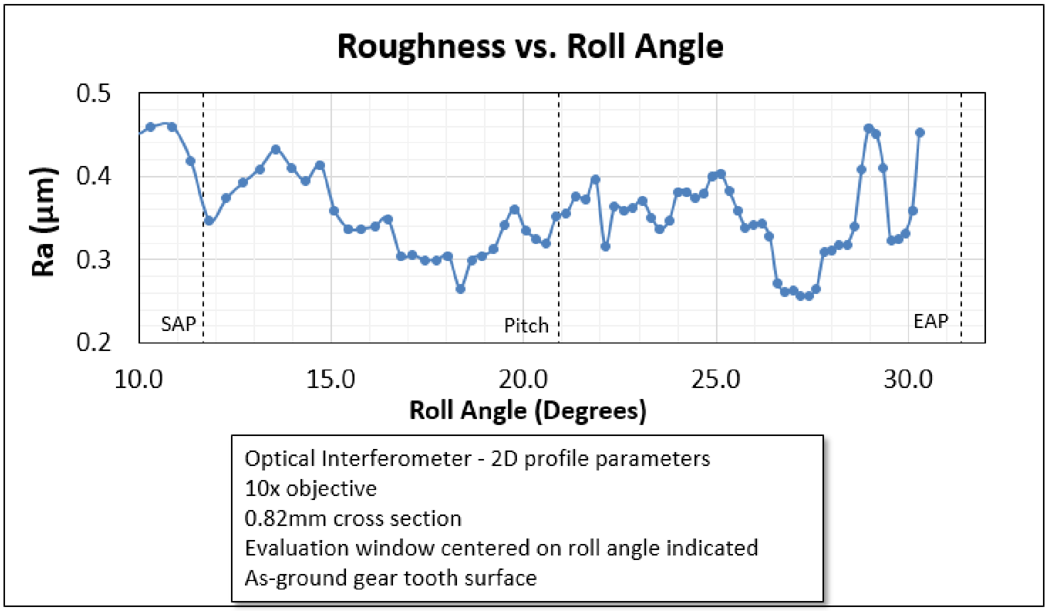


Figure 13 - Roughness vs. roll angle of an as-ground gear tooth surface

7.2 Attenuation of Long Wavelength Roughness Components by Scan Window Size

Another potential shortcoming of using a small interferometry scan window is the attenuation caused by the scan window size. The upper and lower cutoff wavelengths specified by ISO, implemented through a Gaussian phase-correct filter, act as a bandpass filter which removes both long wavelength (form and waviness) and short wavelength (stylus and instrument effects) from the roughness profile. It should be noted that the cutoff wavelengths indicated are not a "hard" cutoff. The Gaussian filter cutoff instead indicates the wavelength where 50% amplitude transmission is achieved, as shown in Figure 14. This excerpt from ISO 3274 has been marked with colored bands to show the cutoff wavelengths used in this effort. The wavelengths between the colored bands are allowed to pass through the filer with the percentage amplitude transmission indicated on the vertical axis. Figure 14 also shows that the scan window of the 10x objective lens has a minimal effect on the transmission band specified by ISO for the ISF surface. The lower cutoff transmission band for the as-ground and peened surfaces however is significantly impacted by the scan window size. This provides another reason for using an interferometry scan window long enough to fully represent the evaluation length prescribed by ISO standards.

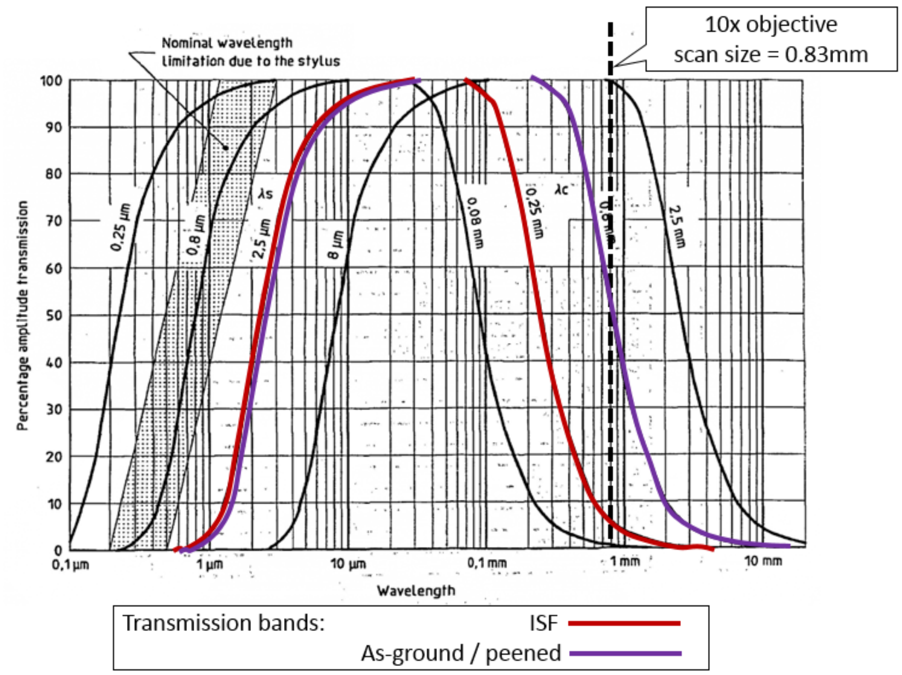


Figure 14 - Gaussian filter transmission characteristics (from ISO 3274, with markups)

7.3 Testing the Effect of Interferometry Scan Lengths

In order to test the effect of interferometer scan lengths on roughness parameters, a scan of the entire profile of one as-ground tooth was taken using the 20X objective lens. A mask was then used to selectively process a portion of the data representing a more limited scan window size. The center of the scan window was centered on the pitch line to simulate the profilometer measurements. Four measurements of two dimensional cross sections evenly spaced across the scan window were then taken for computation of roughness parameters. The mask window size was varied to examine the effect on the results, as shown in Figure 15 and Figure 16. The effect of scan window size is most noticeable in the effect on Rz, where shorter scan lengths result in values that are significantly lower than profilometer measurements. At scan lengths of 2.5 - 3mm, both Ra and Rz values fall into agreement with the profilometer readings. Figure 14 also shows that a 3mm scan length will have much less of a tendency than a 0.83mm scan length to cut longer wavelength components that would otherwise be allowed to pass through the lower cutoff Gaussian filter.

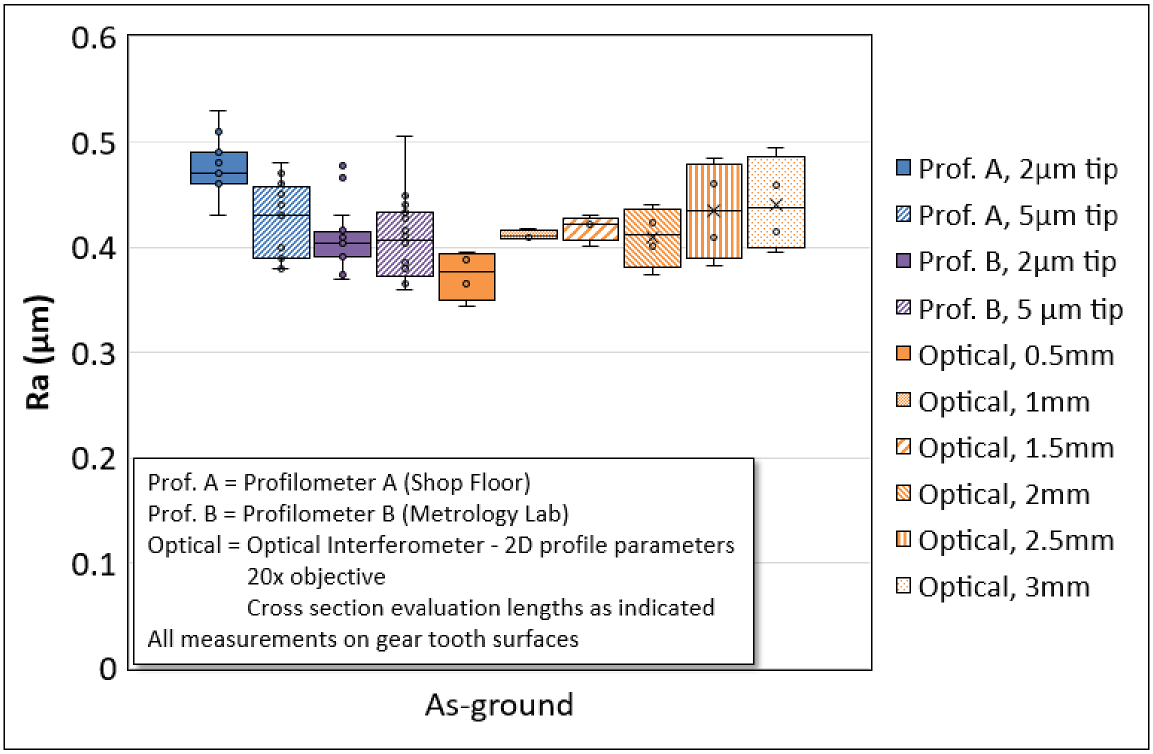


Figure 15 - Effect of scan length on Ra

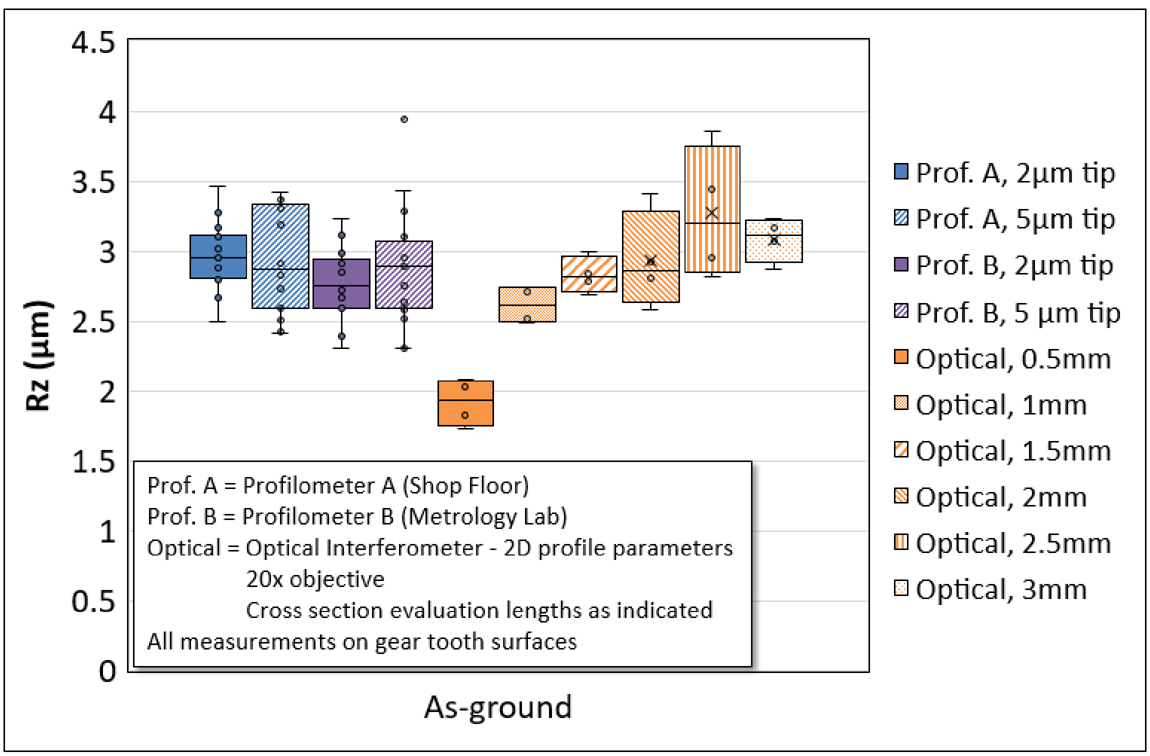


Figure 16 - Effect of scan length on Rz

7.4 Effect of Interferometer Objective Lens Selection

As previously presented in Table 5, several objective lenses were available for use on the interferometer. When selecting an objective, the spatial sampling and optical resolution of the system must be evaluated against the features to be measured. Optical resolution is a parameter which quantifies the ability of the optics in the system to identify two objects that are close together, below which diffraction will cause the objects to be indistinguishable from one another. The numerical aperture of the objective and wavelength of the light source are used to calculate optical resolution. Spatial sampling is computed based on the field of view of the objective and the number of data points collected by the system, essentially indicating the lateral measurement size captured by one measurement point. [20]

Evaluation of these parameters showed that the first series of measurements using the 10x objective had optical resolution and spatial sampling parameters of 0.95μm and 0.81μm, respectively. This is in contrast with the lateral resolution of the profilometer measurements of 0.16 - 0.5 μm (Table 3).

To investigate the effect of objective selection, one tooth was chosen from each surface condition and measured using the 2.75x, 10x and 20x objectives. A 3.3mm scan was taken along the profile of each tooth centered on the face width, which required utilizing the measurement stitching functionality of the system. The 3.3mm scan size was determined to be the data size limit of the digital filtering algorithms in the post processing software. Since stitching together multiple scans can be time consuming, 3XCSI mode was used to speed up measurement time by approximately a factor of three. This results in a decrease in vertical resolution when compared to CSI mode as shown in Table 5, with the vertical resolution in 3XCSI mode being similar to the vertical resolution of profilometer A as shown in Table 3. Four measurements of 3.0mm cross sections evenly spaced across the scan window were then taken for computation of roughness parameters.

Figure 17 and Figure 18 detail the results of the objective testing. For both Ra and Rz, the increased spatial and optical resolution offered by the higher magnification objectives yield higher roughness measurements that are more in agreement with the stylus measurements. The only exception to this were the Rz measurements of the as-ground surface using the 2.75x objective, which had skewed values from noise due to unresolved data points. The lower numerical aperture of the 2.75x objective meant that many of the sloped asperities of the as-ground surface were difficult for this lens to detect.

The outcome of this investigation was that the 20x objective using 3XCSI measurement mode was the best choice for these measurements and yielded results closest to the baseline profilometer data. One tradeoff of this objective lens is the smaller scan window, which leads to longer scan times for a given overall scan length as shown in Table 5. This is one disadvantage of optical interferometry, the scan time (approximately 5 minutes in this case) is significantly longer than the time needed to obtain a profilometer trace, which in the author's experience is on the order of 10 seconds or less. Also, the time needed to produce tooth replicas needs to be considered when evaluating the time required to complete interferometry measurements.

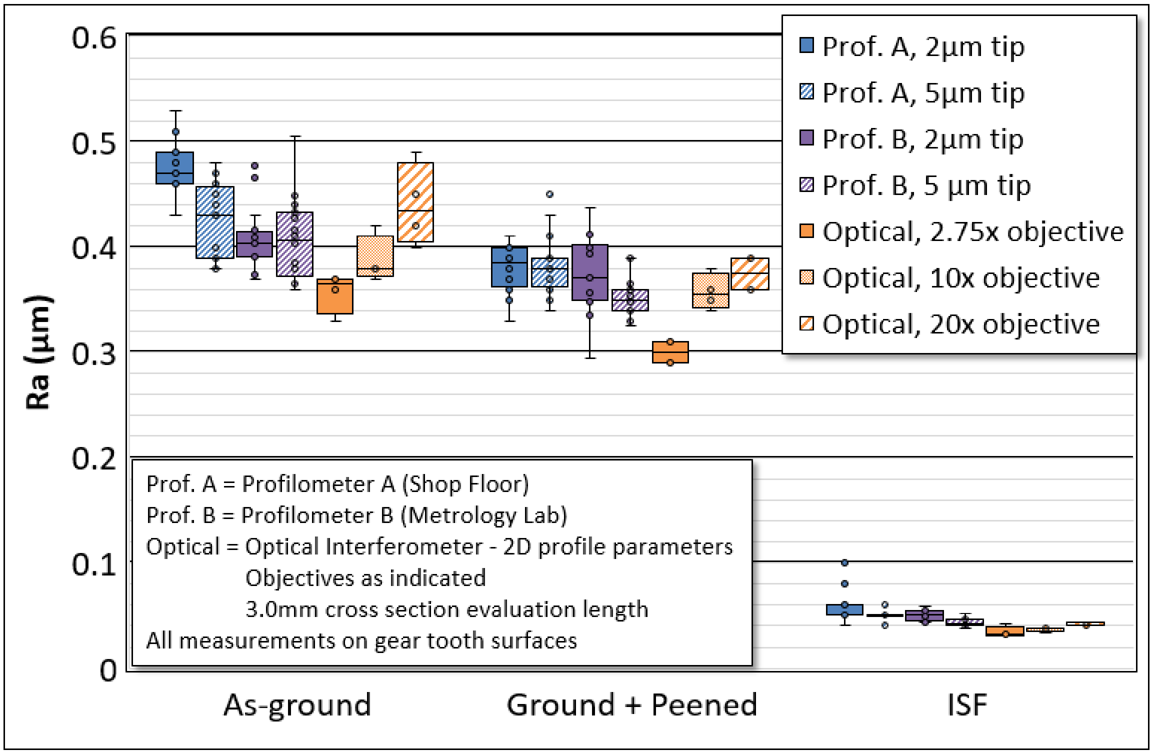


Figure 17 - Objective lens selection effect on Ra

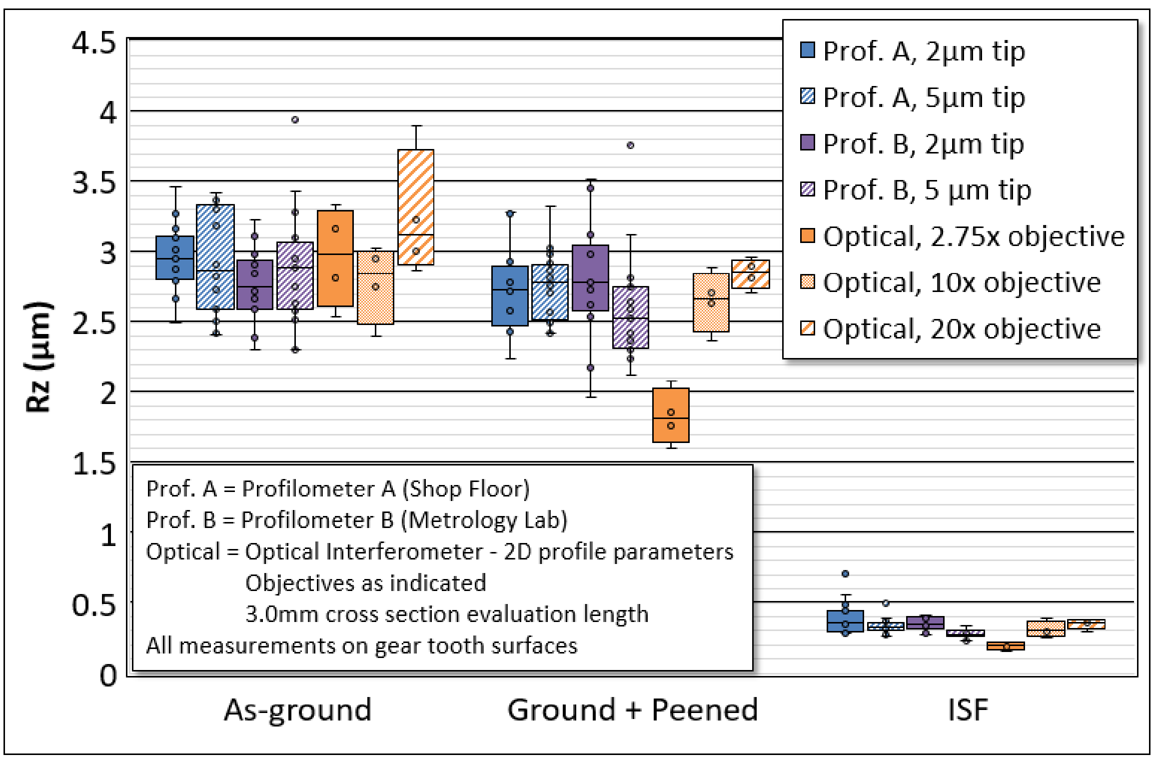


Figure 18 - Objective lens selection effect on Rz

7.5 Hard Epoxy Replica Investigation

It has been the experience of the authors that the hard epoxy compound accurately replicates gear tooth flank roughness on both as-ground and ISF finishes when measured via stylus profilometry. For this reason, the high roughness values from the optical interferometry of the ISF surface hard epoxy replicas were unexpected.

To verify replication performance, one hard epoxy casting was selected from each surface finish and measured using Profilometer A as shown in Figure 19 and Figure 20. These plots show one stylus measurement taken from one replica from each surface finish, compared against the four stylus measurements taken with the same profilometer on the same teeth from which the replicas were made. When considering both Ra and Rz, the replica stylus measurements fall within the range established by the stylus measurements of the teeth for all surface finishes. This suggests that the high roughness readings are related to the interaction of the replicas with the interferometer.

Optical microscopy was then used to further investigate the hard epoxy replicas. This revealed that the replica surfaces are not completely opaque, but rather are somewhat translucent near the surface with underlying features at varying depths. Optical microscope images using two different lighting techniques illustrate this effect in Figure 21, where light penetration from the side of the replica shows the varying opacity of the material. One possibility is that the interferometer has difficulty properly identifying the surface of the replica, leading to incorrect measurements. Further testing is needed to better understand the nature of the subsurface features, and to determine if they are caused by porosity or other characteristics of the replica compound. Also, future work includes researching other hard epoxy compounds that might interact more favorably with optical interferometry measurements.

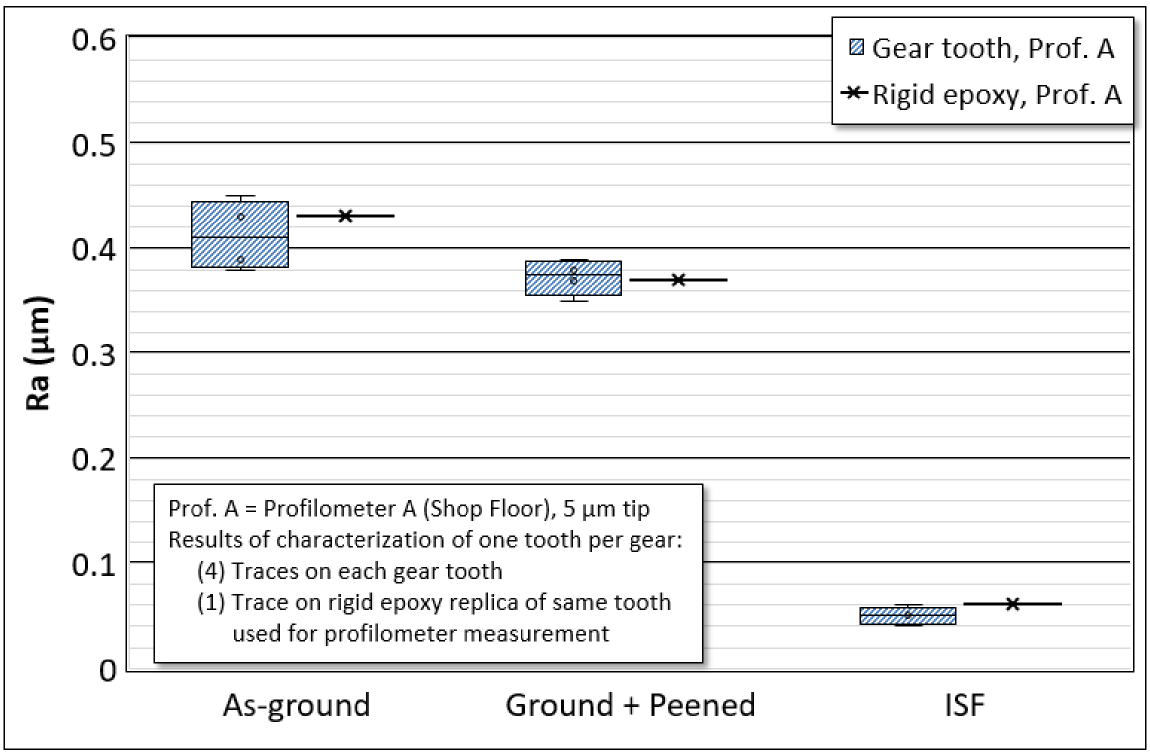


Figure 19 - Ra comparison, rigid epoxy vs. gear teeth

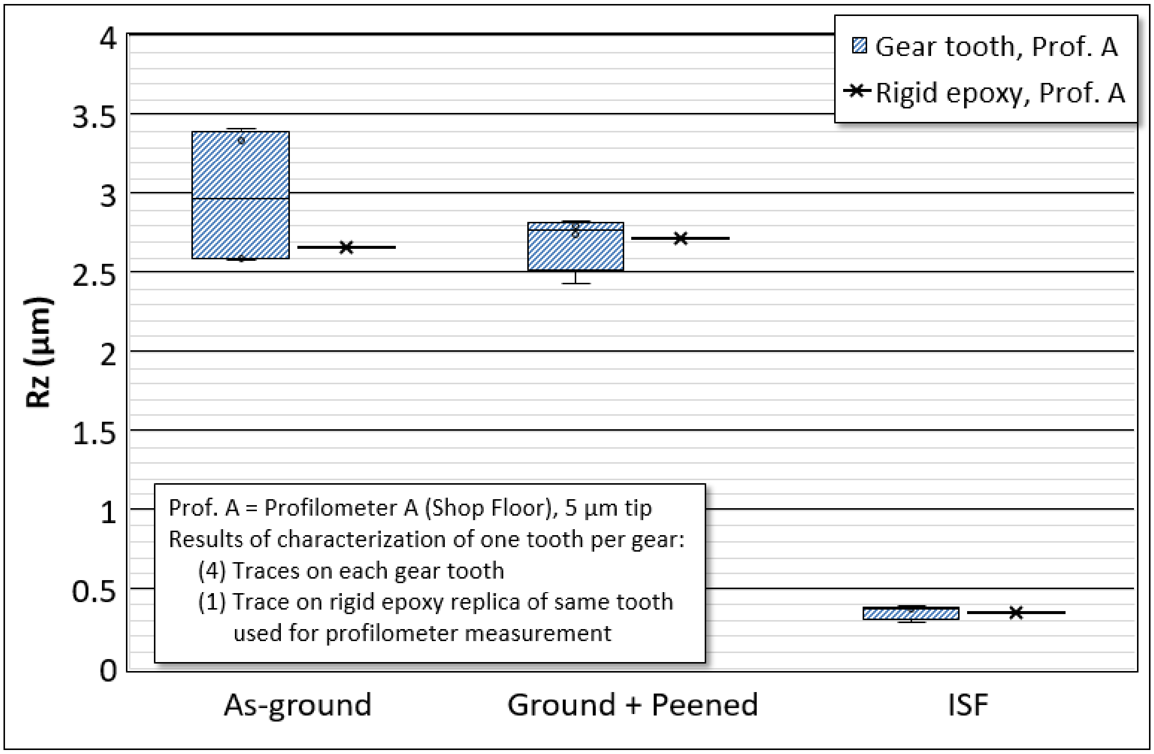
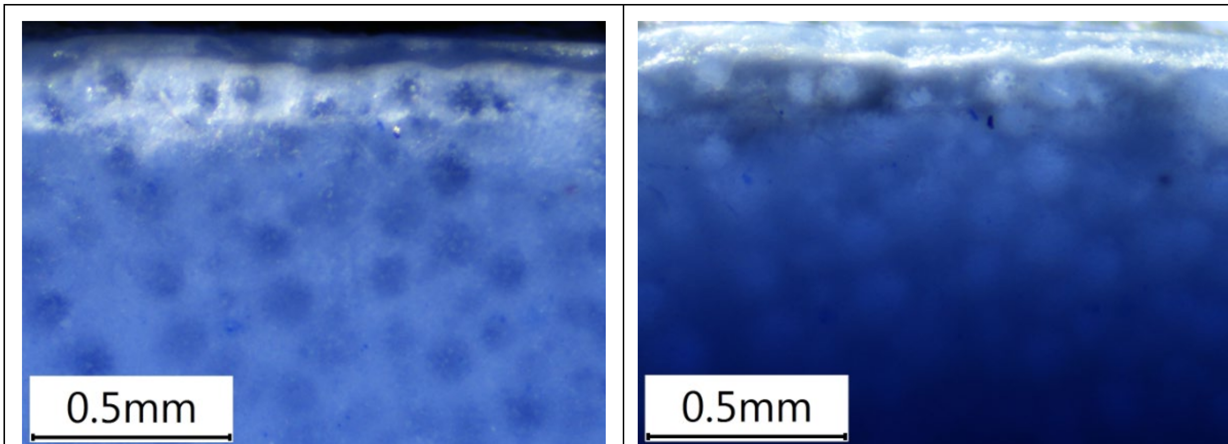


Figure 20 - Rz comparison, rigid epoxy vs. gear teeth



(a) (b)

Figure 21 – Hard epoxy replica of ISF surface with (a) light source normal to surface shown and (b) light penetration into sample from side lighting

8 Conclusions/Future Work

In conclusion, this study tested stylus and optical interferometry roughness measurement methods across as-ground, as-ground / shot peened, and isotropic superfinished (ISF) surfaces. Two different types of replicas of each surface were also measured. The following conclusions are offered:

- Optical interferometry, when used properly, yields measurements that correlate well with stylus profilometry data. The following considerations must be taken into account when planning interferometry measurements:
  - An interferometer objective lens must be chosen than has adequate optical resolution and spatial sampling to capture the roughness features under consideration.

  - A scan length must be chosen that captures variations in roughness along the tooth profile.
  - The scan length must be long enough so it does not to attenuate longer wavelength roughness features. Ideally a scan length equal to the evaluation length recommended in measurement standards would be used, although this is not always possible.
  - Optical interferometry measurements are more time consuming than stylus profilometer measurements. This is due to longer scan times, as well as the effort required to produce tooth replicas.
- Stylus profilometer measurements can be influenced by stylus tip radius, therefore the stylus tip radius should be chosen to conform to the appropriate measurement standards.
- Longer stylus evaluation lengths can average variations in roughness along the tooth profile, however with smaller module gears achieving the recommended evaluation length is not always possible.
- Silicon rubber compound was successfully used to cast replicas of gear teeth for surface roughness evaluation:
  - Silicon rubber replicas yielded interferometer measurements consistent with gear tooth measurements for all three surface finishes tested.
  - An advantage of the silicon rubber material is that it easily releases from the tooth space, however a disadvantage is that it cannot be used for stylus measurements.
- Hard epoxy compound was successfully used to cast replicas of gear teeth for surface roughness evaluation:
  - Hard epoxy replicas of as-ground and as-ground / shot peened surfaces produced optical interferometry results that were consistent with gear tooth measurements.
  - Hard epoxy replicas of ISF surfaces yielded rougher than expected measurements when using optical interferometry. Further investigation showed that the replicas were slightly translucent, which is thought to have interfered with the interferometry measurements. Further investigation into this effect is needed. Stylus profilometry measurements of the replicas were within expected limits which verified the replication performance of the hard epoxy compound.
  - An advantage of the hard epoxy material is that it can be used for stylus measurements, however a disadvantage is that the gear must be chilled to allow the replica to be removed from the tooth space.

Follow-on investigation into the preliminary results yielded the interferometry measurement parameters shown in Table 8. Future work will include measurement of all four teeth from each gear using the newly developed methodology outlined, as well as investigation into other hard epoxy replication compounds that may interact more favorably with optical interferometry measurements.

Table 8 - Final parameters for optical interferometry measurements

	As-ground, As-ground + shot peened	ISF
Filter Low Wavelength (mm)	0.8	0.25
Filter High Wavelength (µm)	2.5	2.5
Minimum Scan Length Along Profile (mm) *Approximately centered on pitch line	3.3	1.5
Scan Data Cross Section Evaluation Length (mm)	3.0	1.25
Scanning Mode	3XCSI	
Z Resolution	High	
Averaging	None	
Filter Type	FFT Fixed	
Filter Cutoff	Gaussian	
Filter	Band Pass	
Form Removal	None	

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