Measurement of Surface Roughness

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This paper describes an experiment designed to quantify the measurement performance of the GelSight Mobile system on measuring surface roughness. The experiment uses the GAR Cast Microfinish Comparator C-9 reference specimen, shown in Fig. 1(a), which has nine regions with roughness values ranging from 20 microinch to 900 microinch Ra. The specimen was calibrated by Holts Precision Inc. in South Windsor, CT, a measurement lab that is certified by the National Institute of Standards and Technology.

The measurements in this study were captured using the GelSight Mobile 0.5X system, shown in Fig. 1(b), which is a 3D surface measurement device that uses a proprietary gel cartridge to enable the measurement. The gel cartridge can be used for hundreds of measurements if care is taken to clean the parts before measurement and not press the device into sharp components. However, the gel cartridge is a consumable in the system and will need to be replaced when the image quality becomes degraded. The system is calibrated when the gel cartridge is replaced and the software provides a simple validation protocol to assess spatial (XY) and depth (Z) accuracy on a calibrated validation specimen. Three gel cartridges were used in this to compare the stability of the roughness measurement across cartridges and calibrations.

The experiment described in this paper is a type 1 gage study where a single operator measured the regions of the reference specimen ten times to assess bias and accuracy. This experiment was repeated with three different gel cartridges. The results were compared to the calibrated values to provide an estimate of global uncertainty in the roughness measurement.

All 3D measurements and analysis results were captured using the GelSight Mobile software. The system was calibrated following the automated calibration protocol in the Mobile software.

(a) GAR C-9 Microfinish Comparator *(b) GelSight Mobile 0.5X Probe*

Figure 1 *(a) Test specimen used in this study, GAR C-9 Microfinish Comparator. The specimen was purchased with a certificate of calibration from Electroformers Inc.*

Region	#1	#2	#3	#4	#5	#6
Ra (μm)	0.58	1.60	3.01	4.97	7.66	11.77
Ra (μin)	22.8	63.0	118.5	195.7	301.6	463.4

Table 1 *The calibrated roughness values from GAR C-9 specimen in microns (μm) and microinch (μin) for the first six patches.*

ROUGHNESS ANALYSIS

The Microfinish Comparator C-9 from GAR Electroforming has nine regions with different average roughness values between 0.5 μm to 22.9 μm Ra, or 20 μin to 900 μin Ra. The certificate states that patches with nominal values between 0.51 and 7.62 μm Ra are analyzed using five cutoffs at 0.8 mm each and patches with nominal value of 10.67 to 22.9 are analyzed using one cutoff at 2.5 mm. The gage used was certified to ISO 9001:2015, ISO 10012-1, ANSI/NCLS Z540-1 and ISO/EIC 17025:2017 with an estimated uncertainty of 50 microinch. The certificate also states that the GAR surface roughness gage is intended for visual / tactual comparison only and should not be used with an electronic profilometer.

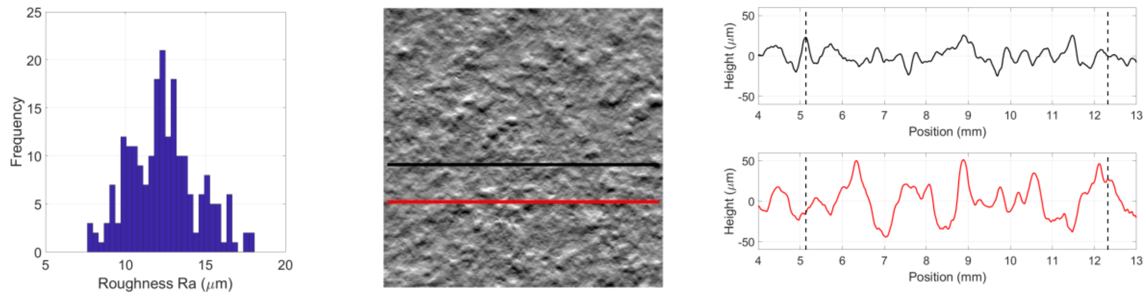
For the roughness analysis, each region was measured ten times. The perimeter of the region was automatically identified and a polynomial form removal with order 4 was applied before calculating the average roughness. Within each region, profiles were extracted at a spacing of 0.1 mm and filtered using the cutoff for the region specified on the calibration certificate (0.8 mm or 2.5 mm). The Ra calculation (average deviation) was performed only within the valid portion of the profile by removing half the cutoff length on each side. The median roughness value across all profiles was returned as the roughness for the region.

This roughness specimen has surface texture that varies quite a bit depending on where the height profile is calculated. As an example, consider the measurement of the 10.67 μm region shown in Fig. 2(b). Two different profiles (black and red) are extracted and filtered to produce the roughness profiles shown in Fig. 2(c). The valid region is shown between the dashed lines. The roughness Ra for the top profile is 8 μm because the profile misses many of the large bumps of the surface. The roughness Ra for the bottom profile is 18 μm. This example illustrates why a single profile is often insufficient for characterizing surface roughness for many surfaces. The distribution of roughness Ra values across 200 profiles is shown in Fig. 2(a). The median is used to characterize the distribution since it is non-Gaussian and often has outliers.

Large surface bumps on the three largest regions, 14.22, 18.29 and 22.86, cause the Ra calculation to have a wide standard deviation and large variation from the value on the calibration certificate. Further investigation is required to determine how the value on the certificate is calculated. For this study, the first six regions are used since the surface texture is closer to isotropic.

ACCURACY STUDY

Three gel cartridges were calibrated using the standard calibration procedure in the GelSight Mobile software. The six regions of the GAR C-9 specimen were measured ten times each for a measurement set of 60 measurements per cartridge.



(a) Roughness histogram *(b) Two profiles extracted from region* *(c) Roughness profiles*

Figure 2 (a) Histogram of profiles extracted horizontally at 0.1 mm increments from top to bottom. (b) Locations of two profiles from the region. (c) Roughness profiles after filtering with a 2.5 mm cutoff. The roughness value Ra of the top profile is 8 μm and the roughness Ra of the bottom profile is 18 μm. The median roughness value is Ra 12.2 μm.

For each measurement, the roughness was calculated using the algorithm described above. The results were exported from the GelSight mobile software in CSV format and loaded into Excel.

From the ten roughness measurements and the calibrated value in Table 1, the standard uncertainty u was calculated as follows:

$$u = \frac{s}{\sqrt{n}}$$

Where s is the estimated standard deviation and n is the number of samples, in this case 10. The expanded uncertainty U is calculated by multiplying the standard uncertainty by a coverage factor k to provide a specific level of confidence, usually 95 or 99 percent [1]. Due to the limited number of measurements being used in the statistical analysis, the coverage factor is chosen from the t-distribution with $n-1$ (e.g., 9) degrees of freedom [2]. The coverage value k_{99} for 99 percent confidence with 9 degrees of freedom in the t-distribution is:

$$k_{99} = 3.25$$

	Roughness Ra (μm)						Roughness Ra (μin)					
	#1	**#2**	**#3**	**#4**	**#5**	**#6**	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**
mean	0.7	1.3	2.7	5.1	7.1	12.5	25.6	52.3	105.2	200.9	278.2	491.6
bias	0.1	0.3	0.3	0.1	0.6	0.7	2.8	10.7	13.3	5.2	23.4	28.2
unc.	0.002	0.01	0.01	0.03	0.05	0.13	0.08	0.27	0.29	1.14	1.92	5.22
U_{99}	0.01	0.02	0.02	0.10	0.16	0.43	0.27	0.89	0.95	3.72	6.23	16.97
U_g	**0.07**	**0.27**	**0.34**	**0.16**	**0.61**	**0.84**	**2.81**	**10.7**	**13.3**	**6.4**	**24.2**	**33.0**

Table 2 *The global uncertainty* U_g *is calculated by summation in quadrature of the bias and 99% confidence level expanded uncertainty* U_{99}*. All values on the left side of the table are in microns and values on the right side of the table are in microinches.*

The bias is calculated as the difference between the mean m of the ten measurements and the known value C from the calibration certificate, used as the true value:

$$b = m - C$$

Note that the value from the calibration certificate has its own uncertainty of 50 microinch, which is not considered in this analysis. The global uncertainty U_g is calculated by summation in quadrature (square root of sum of squares) of the expanded uncertainty and bias:

$$U_g = \sqrt{{U_{99}}^2 + b^2}$$

The results for one of the cartridges are shown in Table 2 in both microns and microinches. The mean m, bias b, standard uncertainty, expanded uncertainty U_{99} are used to calculate to the global uncertainty U_g as defined in the formula above.

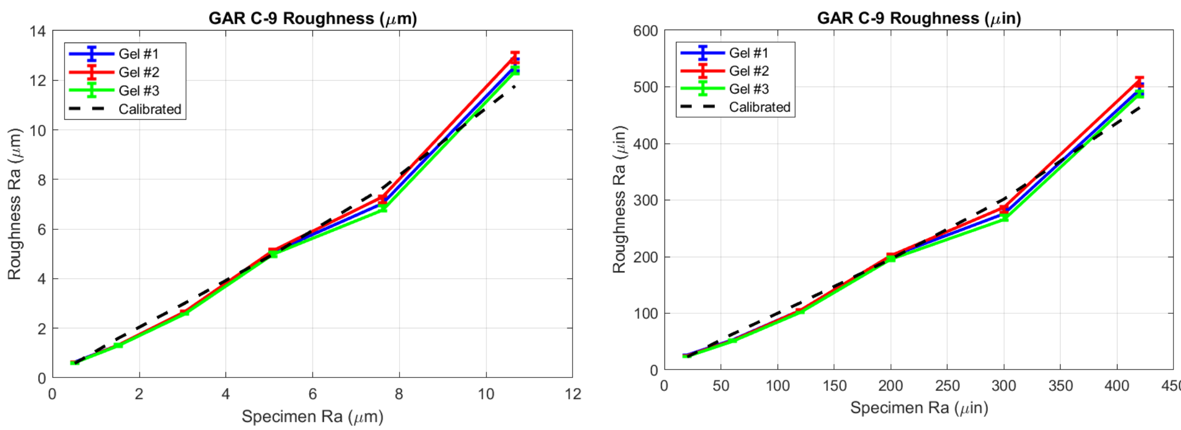


Figure 3 *The measured Roughness Ra for six patches from the GAR C-9 specimen in micron (left) and microinch (right).*

The estimated roughness values for three gel cartridges and each of the six regions are shown in Fig. 3. The error bars on the plots show the 25th and 75th percentiles of the measurements. The calibrated value is shown as the black dashed line. The measured values correlate well to the know values and there is not a large variation in the roughness between gel cartridges. The plots show the same results in both Metric and Imperial units.

The global uncertainty results from all three cartridges of the study are shown in Fig. 4. The results for each cartridge are similar in trend with some variability on specific measurements. Note that the measurements were performed without using the image alignment setting (the default configuration).

By comparing the individual components of the global uncertainty as shown in Table 2, it is clear that the measurement bias is the primary contributing factor to some of the larger uncertainties. It is also clear that the global uncertainty increases with the Ra value.

In general, the uncertainty grows with the nominal size of the feature. This observation is consistent with the measurement principle of the GelSight Mobile probe. The photometric stereo method estimates the surface normal (slope) at every pixel of the image. The slopes are integrated to calculate the depth and any errors in slope estimation are accumulated into errors in the depth estimation. Larger depths will lead to larger errors due to the accumulation of errors.

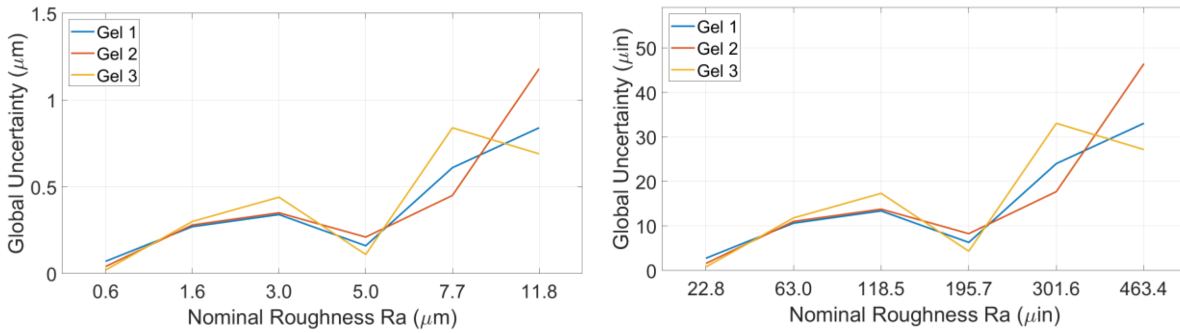


Figure 4 *The Global Uncertainty of surface roughness measurements for the six patches from the GAR C-9 specimen in micron (left) and microinch (right). Note that the uncertainty increases with Ra but is below the 50 microinch uncertainty mentioned on the calibration certificate for the specimen.*

SUMMARY

This report describes a measurement system analysis study for quantifying the accuracy of measuring surface roughness using the GelSight Mobile 0.5X system. The roughness comparator is available from GAR Electroforming so that users can perform their own measurement studies to compare to the results described in this report.

REFERENCES

[1] Bell, Stephanie. *A Beginner's Guide to Uncertainty of Measurement, Issue 2*. Crown, 2001.

[2] Joint Committee for Guides in Metrology, Working Group 1. *Evaluation of measurement data – Guide to the expression of uncertainty in measurement*, JCGM, 2010.