Measuring skew in average surface roughness as a function of surface preparation

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Abstract

Characterizing surface roughness is important for predicting optical performance. Better measurement of surface roughness reduces polishing time, saves money and allows the science requirements to be better defined. This study characterized statistics of average surface roughness as a function of polishing time. Average surface roughness was measured at 81 locations using a Zygo white light interferometer at regular intervals during the polishing process. Each data set was fit to a normal and Largest Extreme Value (LEV) distribution; then tested for goodness of fit. We show that the skew in the average data changes as a function of polishing time.

Introduction

There are many errors to keep track of when generating an optical surface. The errors are typically subdivided by their spatial frequency and source. The low frequency errors are called figure and form errors. Surface roughness represents the highest frequency errors. Figure errors result from vibrations, work piece deflections or material strain during the manufacturing process. Roughness is from the random irregularities inherent in the manufacturing process [1]. Depending on the severity of these errors the optic could be the wrong prescription or merely have cosmetic defects. Defects from high surfaces roughness can cause a loss of power in transmission or reflection. In cases of high power systems, like a laser system, the heat built up could be catastrophic. However, achieving a smooth surface increases the optic's production time and thus the cost of production. To achieve smooth surfaces while driving down cost new manufacturing or measurement techniques must be developed. A standard method of estimating roughness is to make a series of independent measurements and assume a normal distribution in averaging [2,3]. Typically surface roughness is the root mean square (rms) of your data. Due to the lack of negative values in the rms statistic as the mean approaches zero there is a compression in the minus infinity tail of the normal distribution. This compression leads to skew. Previous work has indicated that this skew causes the normal distribution to overestimate the mode or "most probable" surface roughness of polished surfaces [4]. By applying Largest Extreme Value (LEV) distribution you can more accurately measure the mode surface roughness. This study explores how the distribution of rms surface roughness changes from fine grind to polished.

Experimental Setup

The material polished was Corning's Ultra-Low Expansion glass (ULE). ULE was chosen based on its wide usage in optics manufacturing. The ULE blank consisted of a 150 mm round approximately 25 mm thick. The optical flat was polished using an overarm spindle polishing machine. Aluminum oxide of 30 μm, 15 μm, and 5 μm grits were used for the fine grind on an iron tool. Cerium oxide on a pitch lab was used for final polishing. Measurements were made at regular intervals during the polishing process on a Zygo NewView 6300. The NewView is a non-contact white-light interference microscope profilometer. Several contact and non-contact measurement methods were considered. The NewView was chosen for its ability to automate measurement process. One downside to using the NewView is the surface under measure needs to be reflective. This requires the part to be on the order of 20 nm rms roughness. Given that constraint the NewView could not take data until the early stages of polishing. The sample was measured in a square grid 80 x 80 mm with a spacing of 10 mm for a total of 81 points. Fiducials on the sample were used to help measure the same 81 locations each measurement cycle. The NewView spot size was set to 0.53 x 0.707 mm. The part was aligned during measurement to insure that each point was consistently measured each time. Once the fine grind was completed the ULE blank was approximately 5 microns concave. This was worked out during the polishing process. The final flat had about two waves of error in the figure.

Data Analysis

Due to the large number of sample that were taken (2592 samples total) it is important to automate the measurement process including sample movement, fringe nulling, and focusing. A side effect of the automation process is the occasional measurement saturation, resulting in rms measurements greater than five times the mean. To detect and eliminate these errors a Grubbs' Test was performed to identify outliers of significance level $\alpha = 0.05$. The detected saturation errors account for 7 data points (0.3% of measured data). Once identified the saturation errors were manually corrected. In addition to saturation errors the Grubbs' Test help identify scratches and digs present throughout the manufacturing process. It is standard practice when measuring surface roughness to exclude scratches and. Distributions were fit in Minitab 17.

To evaluate the quality of the distribution fit to the data, the Anderson-Darling (AD) test was preformed. The AD test returns two statists, the AD value and a p-value. The AD test was preformed with a 95% confidence interval. A good fit will have a low AD value and high p-value. The AD value should be considered before the p-value. In this paper a distribution will be considered a good fit when AD is less than 1 and the p-value is greater than 0.05.

Table 1 is a summery of the AD test preformed at each time interval. The data was fit to a normal and LEV distribution at each interval. The grey bars in Table 1 represent 13 omitted data sets to keep the table short. These omitted data sets are bimodal thus don't fit normal or LEV distributions. The green cells indicate a good fit. The key findings from the AD test are that early in the polishing process the rms distribution tends toward normal. Later in the polishing process the rms surface roughness moves toward an LEV distribution. In Table 1 time stamp 910* indicates additional filtering to eliminate edge effects from the polishing process. These points can be seen in Figure 4. This could indicate that with proper masking you can improve the distribution fit. Alternatively it could indicate another region where LEV is not the best fit due to increased infrequent high rms events beyond the positive tail of the LEV distribution.

Table 1: A summery of the results for an Anderson-Darling test on rms surface roughness data at various timer intervals. An AD value <1 and a p-value >0.05 indicate a good fit. Fits that pass this test are shaded green. 910* indicates an additional 4 data points were removed to mask off edge effects from the manufacture process.

			Normal			LEV
Time	Mean	AD value	p-value	Mode	AD value	p-value
20	187.42	0.584	0.124	174.7	1.303	<0.01
40	91.03	1.596	<0.005	85.19	4.284	<0.01
60	90.36	1.552	<0.005	83.05	4.578	<0.01
80	113.37	0.631	0.097	101.8	3.188	<0.01
100	102.0	0.777	0.042	90.30	3.050	<0.01
120	130.0	0.566	0.138	111.4	2.667	<0.01
140	136.59	1.160	<0.005	114.9	6.254	<0.01
430	163.7	4.564	<0.005	115.3	5.793	<0.01
610	16.889	4.829	<0.005	13.51	2.777	<0.01
640	12.687	1.371	<0.005	11.49	0.267	>0.25
670	9.662	2.177	<0.005	9.023	0.312	>0.25
700	10.592	3.160	<0.005	9.752	0.757	0.046
730	13.25	0.755	0.048	12.17	0.676	0.077
760	16.057	1.410	<0.005	13.95	0.211	>0.25
790	12.173	1.252	<0.005	10.62	0.458	>0.25
820	11.943	2.847	<0.005	10.45	1.344	<0.01
880	9.199	4.804	<0.005	8.581	1.663	<0.01
910	8.626	5.600	<0.005	8.041	2.766	<0.01
910*				7.868	0.384	>0.25

In order to help visualize the surface roughness the rms was plotted specially in a heat map as seen in Figures 1-4. Four different polishing times are shown to illustrate the rms distribution changes during the polishing process. Figure 1 shows the surface roughness after only 20 minutes of polishing. This is just enough polishing to enable measurement on the NewView. At this point the surface figure is mostly concave. As seen in Table 1 the distribution is strongly normal.

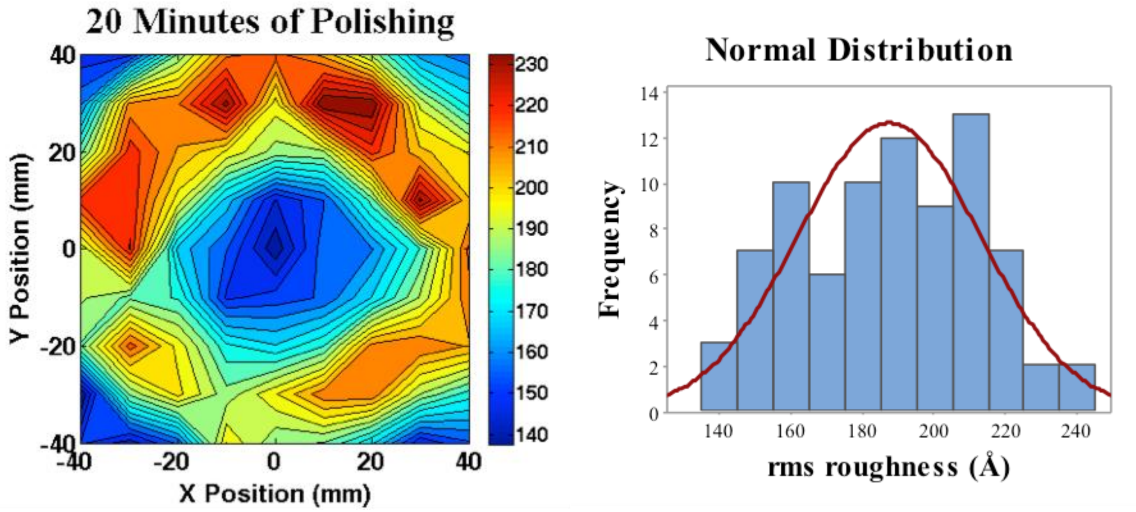

Figure 1: Heat map and histogram plot of rms surface roughness after 20 minutes of polishing. Data has been filtered to remove measurement saturation, scratches and digs. A normal distribution is fitted to the histogram.

As mentioned in above, the omitted time intervals in Table 1 are due to them being bimodal. Figure 2 shows an example and source of the bimodal distribution. As the figure is being shaped the edges of the sample are being polished at a quicker rate than the center.

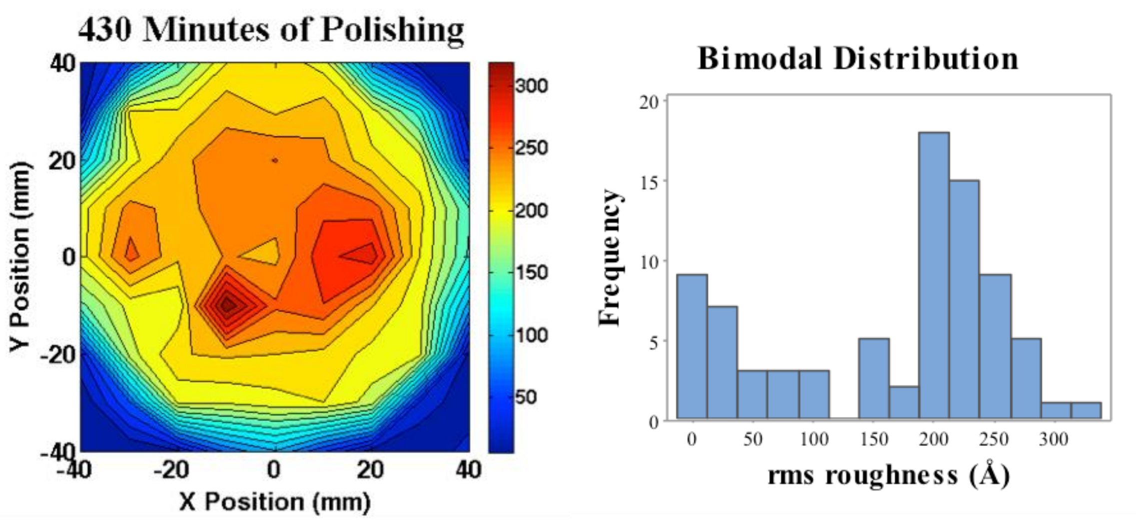

Figure 2: Heat map and histogram plot of rms surface roughness after 430 minutes of polishing. Data has been filtered to remove measurement saturation, scratches and digs. No distribution was fitted to the histogram due to its bimodal nature.

As the figure reaches it final flatness the sample is worked more uniformly. Figure 3 shows a point in the polishing where the distribution largely LEV but still shows some signs of being normal.

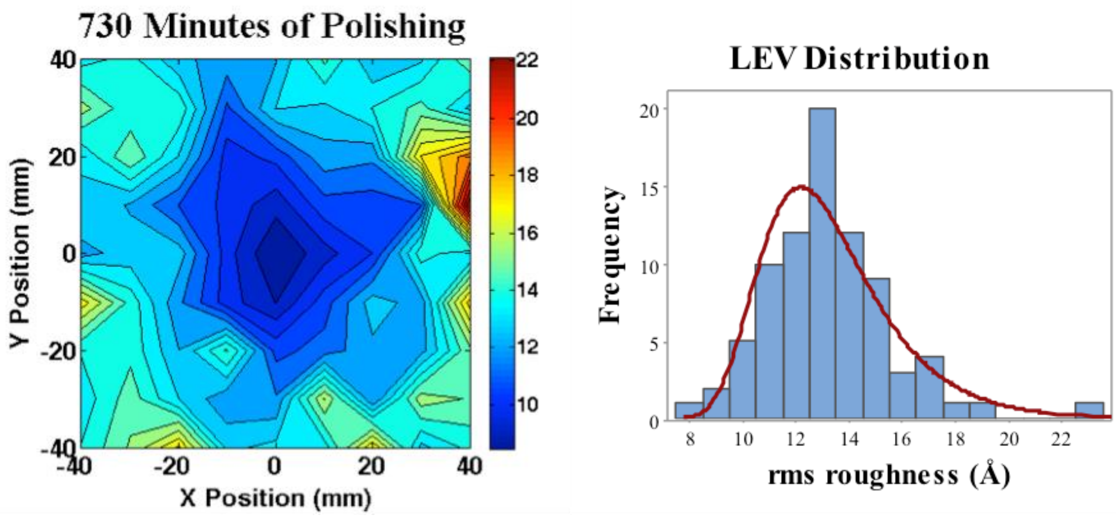

Figure 3: Heat map and histogram plot of rms surface roughness after 730 minutes of polishing. Data has been filtered to remove measurement saturation, scratches and digs. A LEV is fitted to the histogram.

Figure 4 shows the final step in the polishing process for the ULE sample. As seen in Table 1 by omitting the four points in the four corners of the measurement square the distribution fits to an LEV. This may imply that because the sample is circular that the data set should be masked to be circular as well. A circular masking may also help alleviate some issues with the bimodal distribution during the polishing process.

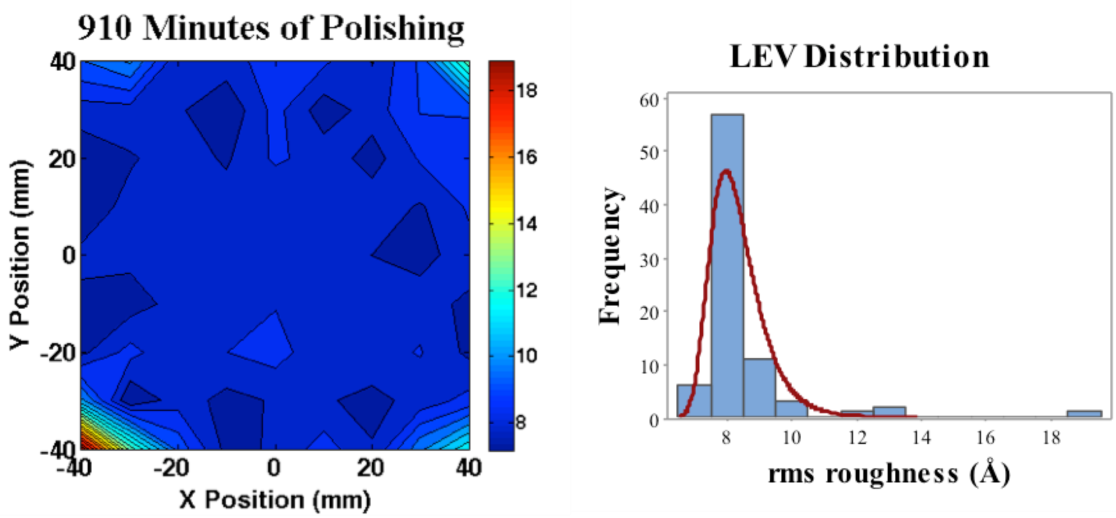

Figure 4: Heat map and histogram plot of rms surface roughness after 910 minutes of polishing. Data has been filtered to remove measurement saturation, scratches and digs. A LEV is fitted to the histogram.

Conclusion

In this study we have shown that the rms surface roughness distributions undergoes changes as a function of polishing time. After the fine grind the rms distribution follows standard surface models maintaining a normal distribution. During the polishing process the mean roughness approaches zero. Due to the fact that rms is a non negative value, the closer to zero the average surface roughness gets the stronger the influence of skew becomes. By applying an LEV distribution to highly polished surfaces a more accurate estimation of the rms surface roughness can be made. Better measurement of the rms surface roughness reduces polishing time, saves money, and allows for better performance predictions.

Future Work

Additional materials will polished and measured. The author currently has plans to polish zerodur, fused silica, silicon carbide (SiC), and BK7. Lessons learned from measurement automation will be applied to lower data saturation issues. Surface roughness data may also be improved by controlling the figure better before the polishing process starts.

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