ABSTRACT
As microlens fabrication technologies proliferate, accurate and accessible metrology techniques are vital to ensure quality. Oft cited interferometric techniques alone can be insufficient and their implementation can be costly. We report on combined contact profilometry and non-contact point-spread function measurement as simple, quick characterization tools for metrological feedback. Their application to quantitative metrics including figure error, roughness, and optical performance are described. Nanometer resolution figure and roughness determination are possible, as well as comparison between measured and theoretical point spread functions. These methods comprise a simple, low-cost, rapid means for characterization of refractive microlenses.

INTRODUCTION
Lens metrology is critical for manufacturing process feedback and system implementation. A variety of techniques are employed for lens metrology, such as interferometry, measurement of the point-spread function (PSF), measurement of the modulation transfer function, and surface profilometry [1]. Interferometers such as Twyman-Green, Mach-Zender and white light are discussed frequently in the literature [2]. However, interferometric techniques can be costly and limited by inadequate spatial resolution and steep angles in high numerical aperture microlenses. Oftentimes, multiple techniques are utilized to fully characterize lens quality (e.g., [3]). In this work we combined a contact metrology tool—a stylus profilometer, with a non-contact method—measurement of the point spread function, to characterize the quality of sub-1 mm injection-molded polymer microlenses, close-packed in arrays. This results in a low-cost, rapid method for evaluation of lens quality. We report on the physical and algorithmic implementation of these techniques as a readily available characterization procedure for microlenses.

MATERIALS AND METHODS
To measure the surface profile of the microlenses, we utilized a stylus profilometer (Mitutoyo SV-3000) with a 2 µm tip radius, 1 µm lateral resolution and 1 nm traverse resolution. The raw profile data was processed using various algorithms that measured figure error and surface roughness. An optical apparatus was assembled to measure the PSF response of the manufactured lenses, a seen in Figure 1.

FIGURE 1. Schematic of the optical apparatus used to measure the point spread function. The laser beam was spatially filtered, collimated and subsequently contracted such that it was incident on the aperture of a single microlens.

In this apparatus, a HeNe laser (Uniphase model 106-1) with output centered at 632.8 nm was spatially filtered and collimated. The radius of the collimated beam was truncated using an iris diaphragm and then further reduced by a telescope comprised of a pair of positive lenses. Uncertainty in the diameter of the truncated beam is 250 µm, which imposes a range on the theoretical diffraction limited PSF for comparison to experimental measurement.

The microlens being tested was attached to a two-axis linear stage perpendicular to the incoming beam. Lastly, the resulting image was magnified by a 60x microscope objective mounted on a translational stage and captured with a CCD (Photometrics, Cascade 650) having 653 x 492 pixels and a pixel size of 7.4 µm x 7.4 µm.
**Figure Error**

Figure error was calculated by comparing the measured surface profile with the desired shape over 80% of the lens aperture. The desired shape was shifted vertically and horizontally with respect to the measured profile in order to minimize the error and determine the optimal fit. The process of fitting the measured profile to the desired geometry is shown in Figure 2.

In the algorithm, the absolute difference between the measured and desired profile was calculated at each data point, and the area under the resulting curve was defined as the error. Once the optimal fit was found, at minimum error, the figure error was calculated as the average absolute difference between the measured and desired profiles.

**Roughness**

The surface roughness was determined by removing the low frequency information associated with the lens’s round shape from the measurement. This was achieved by first dividing the measured profile into segments of equal length and sequentially fitting and subtracting 2nd, 1st and 0th order polynomials to each segment. The average roughness (R_a), defined as the average absolute deviation from the mean [4], was calculated for each individual section. The surface roughness was then calculated as the average R_a of the series of sections.

Dividing the measured profile into the correct number of sections is critical when implementing this algorithm. Using an excessive number of sections will yield a result lower than the actual R_a and vice versa. The optimal section size was determined by using the algorithm to calculate the R_a of various computer-generated spherical profiles with known roughness. The algorithm calculated the correct R_a when these simulated profiles where divided into sections with 40 data points. For our profilometer with 1 µm resolution, this corresponds to 40 µm section width. Thus a surface profile with 1000 µm aperture should be divided into 25 sections and one with 400 µm aperture into 10 sections, etc.

**Point-spread function**

Using the apparatus from Figure 1, we measured the PSF of microlenses manufactured using a variety of processes. One example, for a polymer lens injection-molded into a forged mold, is shown in Figure 3. The measured PSF was aligned laterally to the theoretically predicted PSF and both measurement and theory were normalized as shown.

To evaluate the quality of the microlens’s PSF, we verify that the width of the bright central peak, at full width half maximum (FWHM), falls within the range predicted for a diffraction limited system. For a more detailed description of the mathematical basis for the theoretical PSF, see Hecht [5].

**CONCLUSIONS**

A combination of contact metrology using a stylus profilometer and non-contact measurement of the PSF has been applied to
the characterization of microlenses. The physical and algorithmic implementation of these techniques has been detailed. Figure error measurement relies on fitting of an ideal profile in two-dimensions. Roughness measurement is achieved by dicing the profile into sections of 40 data points each, subtracting polynomials from them, and computing their mean $R_a$. The PSF is aligned to a theoretical function with tolerance band corresponding to uncertainty in the beam diameter measurement. Together, these tools provide a useful, rapid, and relatively low-cost means to characterize the quality of sub-mm refractive microlenses.

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REFERENCES