Dimensional Variation and Roughness Of LIGA Fabricated Microstructures

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Abstract

We have measured the dimensional variation and sidewall roughness of features on PMMA micro-components fabricated by deep x-ray lithography in order to assess the effect of dimensional variation on subsequent assembly operations. Dimensional measurements were made using a stylus profilometer with a repeatability in step height of better than $0.01\text{ }\mu\text{m}$. Roughness measurements were made with the same profilometer scanning in a direction perpendicular to the length of the parts. $22\text{ }\mu\text{m}$ and $54\text{ }\mu\text{m}$ features exhibited dimensional variations described by a Gaussian distribution with standard deviations of $0.202\text{ }\mu\text{m}$ and $0.381\text{ }\mu\text{m}$, respectively. This corresponds to a maximum relative variation of between 0.6% and 0.9%. Sidewall roughnesses were found to be in the range of $0.02\text{ }\mu\text{m}$ to $0.03\text{ }\mu\text{m}$, an insignificant contribution to the total variation when compared to overall dimensional variation. Several potential sources of this variation are discussed, but no single cause was identified as the source of the significant dimensional variation observed here.

Keywords: LIGA, deep x-ray lithography, MEMS, micro-manufacturing, assembly, dimensional variation, roughness

1. Introduction

As deep x-ray lithography (LIGA) emerges as a viable manufacturing technology the understanding and control of dimensional variations become more crucial. All but the simplest micro-devices fabricated by LIGA will require assembly, and thus an understanding of clearances and dimensional tolerances capable of being routinely achieved by LIGA is necessary. Similar tolerance issues will also arise in the development of hybrid micro-systems requiring the assembly of components produced by several different micro-manufacturing technologies. Understanding and control of dimensional tolerance is also important in the development of high throughput, assembly processes. We report here initial results of a study of dimensional variation and sidewall roughness of PMMA micro-components fabricated by LIGA as part of a broader assembly effort. These results indicate that, as for any fabrication process, considerable dimensional variation is present in PMMA micro-components produced by LIGA. These variations are significant for dimensional features in the $20\text{ }\mu\text{m}$ to $50\text{ }\mu\text{m}$ range and are greater than those expected due solely to discretization error in the x-ray masks.

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Despite the strong emphasis on the development of the LIGA fabrication process, there has been little work reported on the magnitude or control of dimensional variation in LIGA. What little has been reported was typically mentioned as part of the fabrication details of a particular micro-system and not a comprehensive study of the variations themselves. For example, Guckel, et. al.^{1,2} have determined that various micro-devices could be assembled with as little as 0.25 μm clearances, suggesting dimensional tolerances of approximately 0.12 μm , although it is not certain whether this represents a minimum of the tolerance range obtained in these structures. Rogner, et. al.,³ in a review of the LIGA process reported 0.5 μm as the smallest 'surface detail', implying a dimensional tolerance of similar magnitude. Sidewall roughnesses were also reported by Rogner, et. al. to be in the range from 0.03 to 0.05 μm . While these and other studies hint at the existence of dimensional variation in micro-components produced by deep x-ray lithography, they do not report directly on the variations themselves.

2. Experimental Methods

2.1 Design and Fabrication of the Micro-Components.

The micro-components used in this study of dimensional variation were part of a more general micro-component insertion assembly experiment. The design of the insert component is shown in Fig. 1A and a scanning electron micrograph of a nickel insert in Fig. 1b. These parts have four arms extending from the corners of a square structure with an overall dimension of 308 μm on a side. Each part, when laying on its side, has two surface parallel to each other and the surface on which it rests. It is these two surfaces which were used as test features to provide dimensional measurements of these structures. This micro-component contains several features which allow straightforward and accurate dimensional measurements to be performed.

Both the micro-components and arrays of matching sockets were produced by deep x-ray lithography. The PMMA parts were produced in an acrylic sheet (100 μm to 500 μm thick) bonded to the substrate. The substrates were previously coated with a sacrificial layer of phosphosilicate glass or silicon dioxide so the individual parts can be released from the substrate. The pattern transfer into the acrylic sheet was done by deep X-ray lithography on the white line beamline (XRLM3) at CAMD⁴. After exposure through an X-ray mask consisting of 2.0 μm thick silicon carbide membrane and 6.3 μm thick Au absorber patterns with a dose of 3 kJ/cm³ at the bottom of the resist, the features were developed in the "GG" developer.⁵ The components were then released from the substrates by etching the sacrificial layer in a buffered 48% HF solution at ORNL. Micro-components produced in two different LIGA runs were included in this study and the variations in each run compared to determine whether any significant run-to-run variation existed.

2.2 Dimensional Metrology Methods.

Performing meaningful dimensional measurements on micro-structures required a highly precise instrument with the ability to measure relatively large dimensions with considerable precision. For these parts, typical overall dimensions were on the order of hundreds of micrometers and measurement accuracy required was better than 0.1 μm . The necessity of meeting both these criteria eliminated many often used metrology tools from consideration. For example, optical microscopy which can measure dimension on the order of hundreds of micrometers, cannot do so with 0.1 μm accuracy. Atomic force microscopy, which easily exceeds this accuracy requirement does not have the range to measure such large overall dimensions. A stylus profilometer,

measuring in the vertical direction, was chosen as the most suitable tool capable of achieving both accuracy and range. The stylus profilometer used in these studies was a Dektak 8000 with a total vertical range of 250 μm with 1 nm resolution. Use of the Dektak had the added advantage of simultaneously providing surface roughness data from the sidewalls of each part.

The 250 μm maximum vertical range of the Dektak profilometer still did not allow direct measurement of overall structure size (308 μm) in these experiments. Instead the difference in height between two parallel surface on each side was used as a measure of dimensional variation. These measurements were made by capturing the part to be measured between the edges of two glass cover slips (each ~ 200 μm thick) on a polished glass substrate as illustrated schematically in Fig. 2. A thin water film was used to hold the cover slips in place after capturing the part. Profilometer measurements were made by starting on one cover slip translating across, up and over the micro-structure and onto the opposite cover slip.

After collecting data, the scan was leveled computationally using two points on the center flat region of the part itself. A typical scan is shown after leveling in Fig. 3. The average height of the center flat was calculated and subtracted from the average heights of parallel flat surface on the two exposed arms at either side of the center flat region. This resulted in two step heights obtained from each scan. The average of these two height values was then used as the measured size of this feature. Treating the data in this manner removed any residual leveling errors remaining in the height measurements. Note that the micro-structure design allowed two possible dimensions to be measured in this way (22 μm and 54 μm), depending on which face of the micro-part was exposed to the stylus.

Roughness measurements were also made using the Dektak stylus profilometer. A sub-micron stylus was used in these measurements to assure inclusion of the higher spatial frequencies. Roughness measurements were made, perpendicular to the length of the part, scanned by the stylus during the dimensional measurements. Three measurements were made, one on the center valley flat, and two on flats at the top of the part and on either side of the valley (see Fig. 2). Root mean square (rms) roughness values were determined for each flat region of each part, and an average and standard deviation calculated.

2.3 Accuracy and Reproducibility of the Dimensional Metrology Methods.

Two experiments were first performed to assess the accuracy and reproducibility of the dimensional measurements reported here. First, a known step height calibration standard (VLSI Standards Inc., Mountain View, CA) was repeatedly measured and the mean and standard deviation calculated. The inherent repeatability of the profilometer, under ideal circumstances, as well as its accuracy were estimated by this experiment. These calibration runs were performed for dimensional measurements of each run. For the first run, results of 22 step height measurements on a 24.27 μm step height standard resulted in a mean value of 23.65 μm ; representing about a 2.5% under deviation from true thickness in the profilometer readings (with a corresponding correction factor of 1.026). Calibration runs for profilometry of the second run resulted in a mean of 24.29 μm , with a resulting correction factor of 0.999. The variation in profilometer measurements using the calibration standard for both LIGA runs, as measured by the standard deviation of the two data sets, was 0.007 μm . These results are summarized in Table 1.

Table 1. Summary of Accuracy and Repeatability Measurements

	LIGA Run	True Value (μm)	Mean (μm)	Correct Factor	Std. Dev. (μm)	Rel. Dev ($=\text{sd}/\text{mean}$)
calibration standard	1	24.27	23.65	1.026	0.007	2.9×10^{-4}
	2	24.27	24.29	0.999	0.007	2.9×10^{-4}
repeat. error	1				0.06	2.5×10^{-3}

Second, two micro-structures were repeatedly mounted and measured using the procedure described above. This experiment was used to determine an upper limit for the reproducibility inherent in the experimental method used here and was only performed for parts from the first run. The repeatability of dimensional measurements after remounting was between $0.06 \mu\text{m}$ and $0.01 \mu\text{m}$, again as determined by the standard deviation of 22 measurements. We will use the worst case of $0.06 \mu\text{m}$ as our estimate of the repeatability error in this dimensional measurement technique.

3. Experimental Results

A total of approximately 100 step height measurements were made on the micro-components from the first run. Parts were randomly chosen from a single processed wafer, mounted as described above, and the step heights between two parallel planes were measured using the stylus profilometer. As a result each measurement involved one of two possible dimensions on each part, either $22 \mu\text{m}$ or $54 \mu\text{m}$, depending on which side of the micro-part was facing up towards the stylus. Thus, results were obtained for both dimensions of the micro-parts, allowing an estimate of how variation scales with feature size.

Dimensional measurement statistics for the two step heights are summarized in Table 2. This variation is approximately described by a Gaussian for all set of micro-components measured. The measurements also indicate a significant variation, as measured by the standard deviation of the measurements, of the features measured on the micro-structures. The magnitude of the variation depends on the feature size and was found to be $0.128 \mu\text{m}$ for the $22 \mu\text{m}$ step feature and $0.348 \mu\text{m}$ for the $54 \mu\text{m}$ step feature. This corresponds to a relative deviation (determined by calculating the ratio of the standard deviation to the mean) of approximately 0.6%, independent of feature size.

Similar results were obtained from the second fabrication run, results of which are also given in Table 2. Here a total of 75 micro-components were measured by stylus profilometry. The dimensional variation was slightly higher for the second run, with a value of $0.202 \mu\text{m}$ for the $22 \mu\text{m}$ step feature and $0.381 \mu\text{m}$ for the $54 \mu\text{m}$ feature. This resulted in a slightly higher relative deviation of 0.94% and 0.71% for the $22 \mu\text{m}$ and $54 \mu\text{m}$ features respectively.

Table 2. Summary of Dimensional Measurements on Micro-Structural Features

Feature	Run	Design Value (μm)	Corrected Mean (μm)	Std. Dev. (μm)	Rel. Dev (=sd/mean)
22 μm step	1	22	22.08	0.128	0.0066
	2	22	21.56	0.202	0.0094
54 μm step	1	54	54.42	0.348	0.0059
	2	54	53.96	0.381	0.0071

Surface roughness results were also obtained for the first LIGA run and the results are summarized in Table 3. Generally average sidewall roughness varied between 0.02 and 0.03 μm rms roughness, depending on where it was measured. The center flat exhibited slightly larger rms roughness than the top flat regions on either side of the center valley. The variation in roughness, as measured by the standard deviation, was quite large for all surfaces representing a nearly 50% variation in roughness levels among the micro-components measured. Some of this variation may be due to damage to the parts during handling as several exceptionally high roughness values are responsible for much of the observed variation. Roughness measurements from the second run are not reported here, but were not notably different than results obtained from the first run.

Table 3. Summary of Sidewall Roughness Results

Location	Average rms Roughness ($\text{\AA}$)	Standard Dev. ($\text{\AA}$)
Top Flats	250	139
	227	96
Center Flat	301	93

It is also interesting to observe that no correlation was observed between roughness values and measured step heights. An example of this is shown in Fig. 4 which is a plot of rms roughness vs. measured height for the 54 μm step. The correlation coefficient (r^2) for these data is 0.02, where 0 represents no statistical correlation and 1 represents complete correlation. This lack of correlation suggests that greater surface roughness is not correlated to larger (or smaller) dimensional measurements. Fig. 4 also shows a few outliers for both roughness and step height measurements; these most likely being parts which were scratched or damaged by handling.

4. Discussion

These experiments have demonstrated a significant dimensional variation in the size of features on PMMA micro-structures. This variation also appears to be dependent on feature size with a standard deviation of between $0.128\text{ }\mu\text{m}$ and $0.381\text{ }\mu\text{m}$ (0.6% to 0.9% relative deviation) for feature dimensions in the range from $20\text{ }\mu\text{m}$ to $50\text{ }\mu\text{m}$. This variation is approximately the same as that implied by other investigators discussed earlier. Average sidewall roughness, measured perpendicular to the length of the parts, was found to vary between $0.02\text{ }\mu\text{m}$ and $0.03\text{ }\mu\text{m}$ here, in agreement with the range of roughness values reported by Rogner et. al. This sidewall surface roughness is much smaller than the dimensional variations and hence do not contribute significantly to the overall assembly tolerance and clearance. Sources of the dimensional variation reported here can be divided into two general classes: variations caused by the x-ray mask and variations caused by the exposure and development processes. These are discussed in greater detail below.

4.1 Variations Caused by the X-Ray Mask.

The x-ray mask fabrication process involves production of a chrome master by e-beam lithography followed by reproduction of the chrome pattern in electroplated gold via an optical photolithography process. Discretization errors can occur during printing of the chrome master due to the finite spot size of the electron beam and process biases associated with the resist masking process. For the present work, a spot size of $0.25\text{ }\mu\text{m}$ was used, hence patterns are built up of pixels $0.25\text{ }\mu\text{m}$ on a side, and the mask vendor specifies linewidth variation no greater than the spot size. However, our experience with various masks made by the same vendor indicate linewidth variation is typically much better, on the order of $0.1\text{ }\mu\text{m}$ or less for masks written with a spot size of $0.25\text{ }\mu\text{m}$.

Other mask fabrication process variables may contribute more significant linewidth variation. Since photolithographic reproduction is used to copy the chrome master, linewidth variation in the resist process employed will contribute directly to variation in the x-ray mask. Typical linewidth variation observed in the 1X lithographic process used is about $0.2\text{ }\mu\text{m}$. Linewidth bias can also occur if the resist is over or underexposed. This will contribute to systematic bias in the x-ray mask but does not necessarily increase linewidth variation.

Electroplating of gold into the resist image can contribute to two types of error in the mask: plating bias and sidewall slope. Plating bias occurs as a result of erosion of the resist flank by the plating chemical. We have tuned our resist/plating process to minimize plating bias, and using SEM we estimate this to be on the order of $0.1\text{ }\mu\text{m}$ or less. Sidewall slope occurs as the electrodeposited gold replicates the flank of the resist image. If the resist image is not perfectly vertical, the resulting absorber top edge is displaced from the physical edge of the image. Since the absorber thickness needs to be about $5\text{ }\mu\text{m}$ for sufficient x-ray opacity, sidewall slope can contribute significantly to mask linewidth error. For example, a sidewall slope of only 5 degrees would displace the top edge of the line by $0.4\text{ }\mu\text{m}$ with respect to the bottom edge, producing a total linewidth uncertainty of $0.8\text{ }\mu\text{m}$. How this translates into the x-ray resist depends on the exact dose and develop conditions. Also, sidewall slope is quite uniform throughout the pattern, and does not show a dependency on image size. Thus any sidewall slope present in our masks would be expected to produce a linewidth bias, but not contribute to linewidth variation. In the present work, we have estimated, via SEM, the sidewall slope to be 1 degree or less, implying a linewidth error of less than $0.1\text{ }\mu\text{m}$ per side.

4.2 Variations Caused by the Exposure/Development Processes.

Swelling of the PMMA is produced by the formation of gaseous species generated during the irradiation process.⁶ It depends on the rate of dose deposition inside the resist and is sensitive to parameters such as current intensity and filtering conditions used for the exposure. Insufficient control of exposure conditions can contribute to geometrical shape distortion of the parts. Out of plane distortions of the mask membrane due to radiation damage and heating of the mask during exposure could also contribute to distortions of the PMMA parts. These masks based on SiC membranes seem to be less resistant to radiation damage than the B-Si membranes.

Several other factors may also contribute to distortion of the PMMA resist. The application of the PMMA sheet is done by a gluing process followed by milling to the final height. Swelling induced by the glue plus thermal coefficient of expansion mismatch of the silicon substrate and mechanical milling combine to create internal stress in the PMMA sheet. Releasing the PMMA parts from the substrate may permit strain in response to this stress, potentially changing the shape or size of the part. This effect would be expected to create dimensional variations in proportion to the size of the part. Stress is also induced by heating of the film during x-ray irradiation. However, since the x-ray exposed area is washed away by developer, it seems unlikely that these stresses would be significant contributors to linewidth variation.

Swelling introduced by developer and water rinses or by ambient humidity may also cause dimensional change. PMMA has been reported to swell as much as 1-2% (H. Guckel, private communication) in response to ambient humidity. However, swelling should result in parts which are oversized rather than undersized, and since all measured parts were equilibrated to the same ambient humidity level, it seems unlikely that swelling contributes significantly to the observed linewidth variation.

While nickel micro-components were not included in this study, it is reasonable to assume that significant dimensional variation will also be found in nickel components fabricated by LIGA. Since PMMA structures act as molds for the nickel electroplating process and this process itself offers additional opportunities to introduce dimensional variation we expect this variation to be as large or larger than the variation observed in PMMA components.

In the absence of a definitive cause of the dimensional variation, considerable care should be taken in extrapolating these results to other size regimes. Strictly speaking, these results are only applicable to PMMA parts and feature sizes in the range from 20 μm to 50 μm . These results do highlight the need for a more detailed study of dimensional variation for other materials and over a broader range of dimensions. In the meantime, dimensional metrology to characterize dimensional variation should be a necessary operation in the assembly of LIGA fabricated components with tight clearances.

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Figure 1a. Schematic diagram of the micro-component used in this study.

Figure 1b. Scanning electron micrograph of a Ni micro-component.

Figure 2. Diagram of the stylus path over the component used to measure step feature size.

Fig. 3. Sample profilometer scan over a micro-component after leveling.

Fig. 4 Plot of roughness and step height measurements showing lack of correlation between these parameters.