Dimensional Errors in LIGA-Produced Metal Parts due to Thermal Expansion and Swelling of PMMA

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The LIGA process employs deep x-ray lithography to pattern a thick PMMA resist that is subsequently developed to remove exposed areas. This produces a non-conducting mold that is then filled by electrodeposition to form either individual metal parts or a tool for molding replicas.

Many factors influence the overall precision of a finished metal part. Dimensional errors may result directly from errors in the PMMA mold due to synchrotron beam divergence, thermal expansion of the mask, fluorescence radiation and photo and Auger electrons. These generally give dimensional errors of at most a few microns between the mask pattern and final part. Errors in the metal part can also result from displacement of the PMMA during the electroforming step [1]. PMMA has a coefficient of thermal expansion of about 8×10^{-5} C^{-1}, so a rise in temperature of 30 C (50 C plating temperature) gives a linear strain of more the 0.2%. Water absorbed in the electrolyte bath may produce even larger strains, up to 0.4% [1,2]. As illustrated in Figure 1, the combined influence of such strains can produce dimensional errors of 10 μm or more in metal parts typical of those produced by LIGA.

To help understand and remedy this problem, we have performed numerical simulations of sidewall displacements for PMMA features of various geometries. These numerical results, computed using the general-purpose finite-element code ABAQUS, were fit to obtain a simple analytical expression for the sidewall displacement at the top surface as a function of the geometry and strain. Based on a Poisson's ratio of $\nu = 0.35$, the plane-strain result for long rectilinear features is,

$$\delta = \varepsilon h \frac{162\omega + 49\omega^3}{240 + 40\omega + 21\omega^3} \qquad \omega = \frac{w}{h} \tag{1}$$

where ε is the total linear strain, h is the PMMA thickness and w is the PMMA feature width. A plot of this function and the numerical solutions is shown in Figure 2. The asymptotic behavior of this expression is

$$\delta \approx 0.68\, \varepsilon w \quad \text{as} \quad \frac{w}{h} \to 0 \qquad \text{and} \qquad \delta \approx 2.33\, \varepsilon h \quad \text{as} \quad \frac{w}{h} \to \infty \tag{2}$$

Lateral displacements thus scale like the PMMA structure width when w/h is small, but scale with the PMMA thickness when w/h is large.

To illustrate the magnitude of this problem, consider a resist of height $h = 250$ μm, a cavity width of $d = 25$ μm, and a total linear strain of 0.007 corresponding to the example given above. For the case of an isolated feature, $w/h \to \infty$, the top-surface lateral displacement for each side of the cavity is $\delta \approx 2.33\, \varepsilon h = 4.08$ μm, so the maximum error in the width of the cavity is

$2\delta = 8.2$ μm and the cavity width is just under 17 μm at the top. This represents a relative error of more than 30%. Note that the top of the cavity would actually close for the same strain and cavity width if the mold height were increased to 1 mm; in this case, $2\delta = 32.6$ μm > 25 μm.

These large displacements can be reduced significantly through the use of auxiliary moat-like channels surrounding a part. Illustrated in Figure 3, such relief channels reduce displacements and the associated taper of part sidewalls by reducing the value of w/h for the PMMA structure bounding the part. From Eq. 1, we see that displacements are reduced from the limit $\delta = 2.33\varepsilon h$ by a factor of 3.3 to $\delta = 0.70\varepsilon h$ when such channels are placed a distance $w = h$ from the part. For a distance $w/h = 0.5$, the displacement is reduced by 6.9, and for $w/h = 0.2$ the reduction is about a factor of 17. We thus conclude that dimensional errors due to PMMA swelling and thermal expansion can be reduced by more than an order of magnitude through the use of these relief channels, without introducing new free-standing structures of very high aspect ratio.

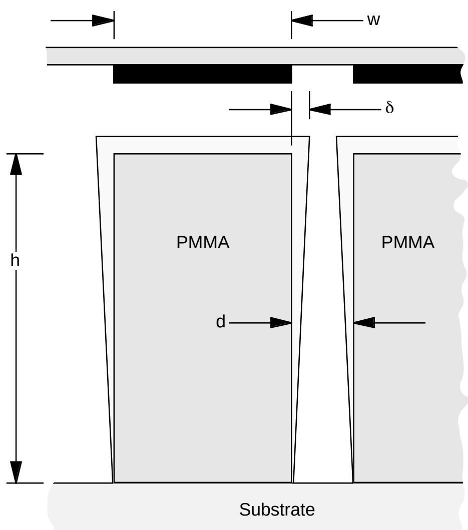


Figure 1. Schematic of sidewall displacements due to expansion of the PMMA. Sidewalls become tapered and slightly curved because the bottom surface is attached to a rigid substrate. Displacements, δ, scale with the height, *h*, when *w/h* is large.

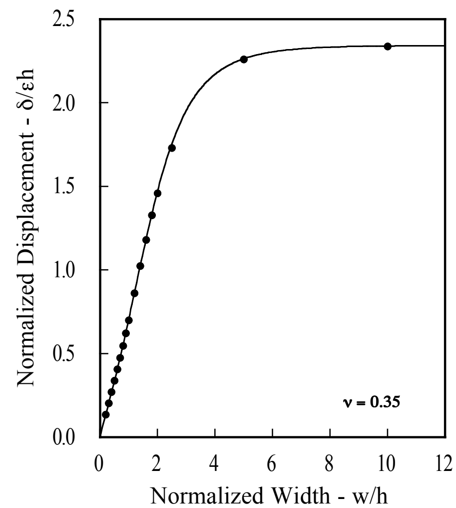
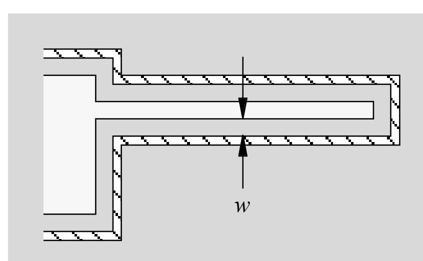


Figure 2. Normalized displacement of top-surface sidewall for rectilinear structures. Displacements grow strongly with increasing width, *w*, of the PMMA structure until the width is about four times the PMMA thickness, *h*.

Figure 3. Relief channel (cross-hatched) patterned into the mask in the region surrounding a part (light) can dramatically reduce sidewall taper if placed sufficiently close to the part. The width of the channel should be at least twice the anticipated displacement given by Eq. 1; a width equal to the PMMA thickness will help ensure that these auxiliary channels do not develop slowly due to transport limitations.



References

1. A. Ruzzu and B. Matthis (2002) Swelling of PMMA-structures in aqueous solutions and room temperature Ni-electroforming. Microsyst. Technol. 8: 116-119.
2. S. H. Goods, R. M. Watson and M. Yi (2003) Thermal expansion and hydration behavior of PMMA molding materials for LIGA applications. SAND2003-8000, Sandia National Laboratories Report.