Dimensional Issues in Stereolithography

David L. Winmill, Daniel M. Hoopes and Suresh S. Jayanthi
DuPont Somos®, Two Penn's Way, New Castle, DE 19720-2407

Abstract

New stereolithography photopolymers have recently been introduced that provide a wider range of functional properties similar to those of high-density polyethylene. One of the important criteria for these materials is the dimensional accuracy and stability in end-use applications as mold masters or the actual functional parts. This work investigates the dimensional stability of one of these new materials with varying amounts of exposure during build. The effect of aging on the part dimensions is reported. The result of environmental humidity extremes at ambient temperature on part dimensions is investigated and compared for parts made from two different families of stereolithography resins, namely DuPont Somos® 7100 and Somos® 8100.

Introduction

Rapid prototyping technologies have gone through several advances in the last few years. Stereolithography in particular has seen some dramatic improvements due to equipment changes and innovations in photopolymers. The primary driving forces for new photopolymers are the quest for improved mechanical properties and dimensional stability.

Prototypes made by stereolithography now offer high resistance to harsh environmental conditions. For example, some of the new materials now provide heat deflection temperatures over 100°C and can also be used in water applications without an appreciable drop in physical properties. More recent stereolithography materials are providing properties similar to commonly used plastics like high-density polyethylene and ABS. All of this has significantly increased the range of applications in which stereolithography can now be used.

To achieve a more enduring growth of these applications, a better appreciation of the changes that can occur in the properties of these materials is needed. The variations in the physical properties with different fabrication strategies, aging under different environmental conditions and endurance testing are becoming more important as these materials are being used to validate not only the design but also the functional intent of the prototypes.

This paper focuses primarily on aspects of the dimensional behavior of these new classes of materials and also highlights some of the technological limitations that we have to live with. In trying to build dimensionally accurate and stable prototypes many issues have to be monitored. These include the nature of the geometry and the subsequent slice files as well as the orientation of the part on the build platform. The aspects that are given more attention here are the stereolithography machine calibration, the photopolymer resin being used, the fabrication style used to build parts, their subsequent post-curing and eventually the environmental conditions that they experience.

The experimental studies reported in this paper are based on two high performance materials for stereolithography. One of these is a high strength, high heat deflection temperature and humidity tolerant material called Somos® 7110. The other is a high flexibility and high impact strength material called Somos® 8100 or 8110 that will be commercialized in the third quarter of this year. This work will first highlight the contribution of machine calibration as a source of error in the production of stereolithography parts. Secondly, it characterizes the influence of laser exposure and post-exposure on dimensional stability. Thirdly, it shows the influence of environmental conditions on the dimensional stability of finished parts. Finally, the findings are summarized and observations are made with the view to improving the dimensional behavior.

Recent Work

In 1997, Paul Jacobs (1) first showed that processes such as stereolithography exhibit non-uniform shrinkage behavior and contain a random noise shrinkage component. Following up on Jacobs' work, Tom Mueller (2) expanded the concepts into a more general model that would include the effects of pattern accuracy as well as the shrinkage of injection-molded plastic. This would allow tolerances to be predicted for the molded parts rather than the tool.

Prior to these two works, significant effort was focused on quantifying the achievable accuracy levels using an industry recognized "User-Part" (3). This particular diagnostic has been used to optimize the compensation factors necessary to improve achievable accuracy. It is also used as a confirmation diagnostic to assess the realistic tolerances achievable in a typical stereolithography machine after all compensation factors have been applied. Figure 1 illustrates the distribution of error across the part for a compensated diagnostic part. As the figure shows there is a high degree (± 6 mil) of random noise. Contributing to the noise are the machine calibration status, process characteristics, possible non-uniform shrinkage behavior of the stereolithography material and the measurement techniques.

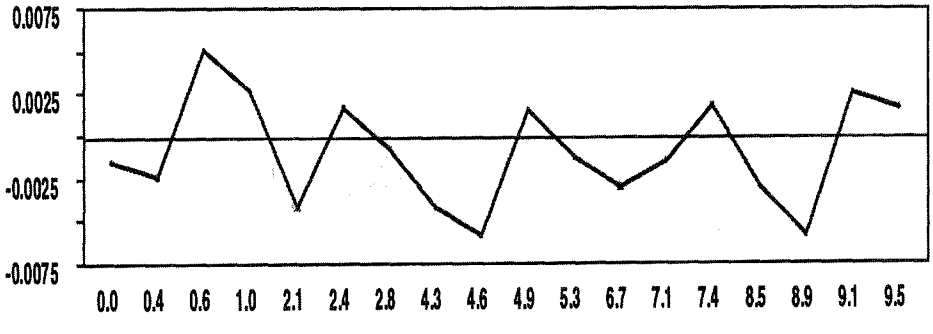

Figure 1: Distribution of Random Noise in a Compensated SL Diagnostic Part
(Measured Error on Y axis; CAD Dimensions on X axis)

System Status and Dimensional Accuracy

In order to investigate the system calibration status and the effect of different exposures on part dimensions, Somos 8100® was used in a 3D System's SLA™ - 500 stereolithography machine. Sixteen square boxes (2 inch by 2 inch) were designed and spaced evenly on the platform in a four by four array. The CAD for the boxes featured sidewalls as well as an internal circular boss and flat panel. Each of the four columns of boxes received a different hatch overcure of –2, 0, 2, or 4 mils whereas all the other build conditions stayed the same. All of these were quite normal, such as 6 mil layers, ACES build style (4 mil hatch spacing), and a box hatch. The boxes were built without any material shrinkage compensation. A beam width compensation of 6 mils was used. Just after the parts were imaged the X and Y dimensions of the boxes were measured and found to be substantially different from the chosen CAD values.

Initial Part Size Variation over the SLA - 500 Platform
(Part minus CAD Dimension in mils)

Row Number	Column Number			
	1	2	3	4
1	7	10	5	2
2	6	9	3	3
3	6	5	5	3
4	7	8	4	2

Table 1: Dimensional differences for the X dimensions of the two-inch square boxes

As shown above in Table 1, the measured X dimensions were all larger than the desired CAD dimension, and the largest errors tended to occur on the left-hand side of the platform. In the case of the Y dimensions (see Table 2 below), all the dimensions were smaller than intended and the greatest errors occurred on the right hand side of the platform. Clearly then, this machine has a poorly calibrated platform. Therefore the initial green state dimensions were taken as the starting point from which to measure any changes that might occur due to aging or post-cure procedure.

Initial Part Size Variation over the SLA - 500 Platform
(Part minus CAD Dimension in mils)

Row Number	Column Number 1	2	3	4
1	-12	-10	-14	-14
2	-12	-11	-15	-15
3	-12	-12	-13	-16
4	-11	-8	-13	-15

Table 2: Dimensional differences for the Y dimensions of the two-inch square boxes

In the future it would seem to be a good idea if the platform calibration was measured with a photo responsive film such as Dylux™ before imaging the parts. The values obtained from this could then be used as the initial values and would be completely free of any effects (expected to be small directly after a build) of the photopolymer resin.

Dimensional Accuracy after Imaging

After measuring the initial dimensions as described above, two boxes from each hatch over-cure exposure were post-cured with UV light for one hour in a 3D Systems' Post Cure Apparatus. A little later the extents, the circular boss and the panel thickness were measured. The results for the extents (see Figure 2) show that the lowest exposures (-2.0 mils hatch over-cure) actually produce an expansion of the parts.

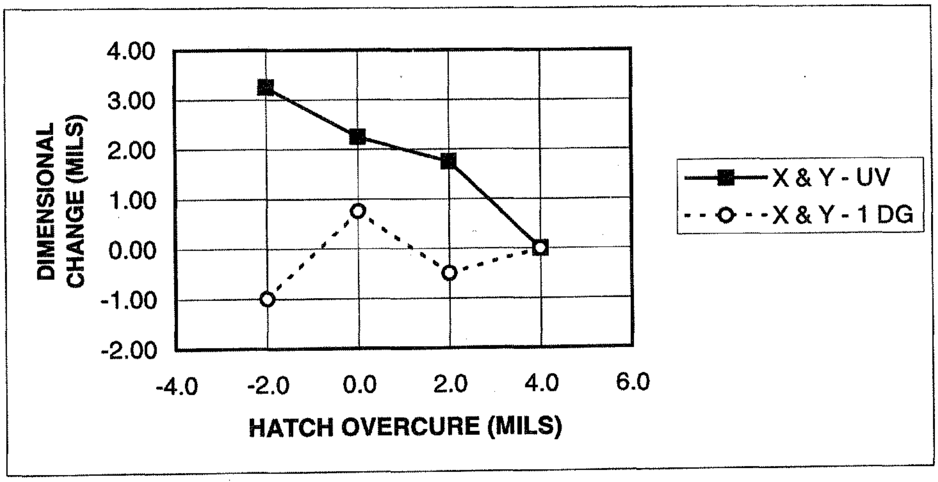

Figure 2: Dimensional Behavior with Different Hatch Over-cures for Somos® 8100

The amount of expansion falls with increasing exposure and reaches zero with 4.0 mils hatch over-cure. The boxes from each hatch over-cure that were not post-cured were left for a day at ambient conditions (labeled 1 DG) and again measured. These data are rather scattered but show a general trend of the lower exposure to cause shrinkage as the parts age in their green state. The circular boss showed similar effects, but the data was noisier due to the smaller dimension. The panel was too thin (80 mils) to determine any dimensional changes in the Y direction.

In order to further investigate the effect of hatch over-cure on dimensional stability in the green state, tensile bars (150 mm long) were measured for four different exposure conditions over a prolonged period of time after imaging (Figure 3). These parts were made on a DuPont Somos® stereolithography machine with 2-mil scan spacing and a raster scan with a spot diameter of about 6 mil. Again the lowest exposures gave the most change, and in the case of parts made with 1 mil over-cure the dimensional change was + 0.8% after 30 days which equates to 8 mil per inch. However, in the case of higher hatch over-cure exposures of 8 and 9 mil, there was almost no dimensional change with time.

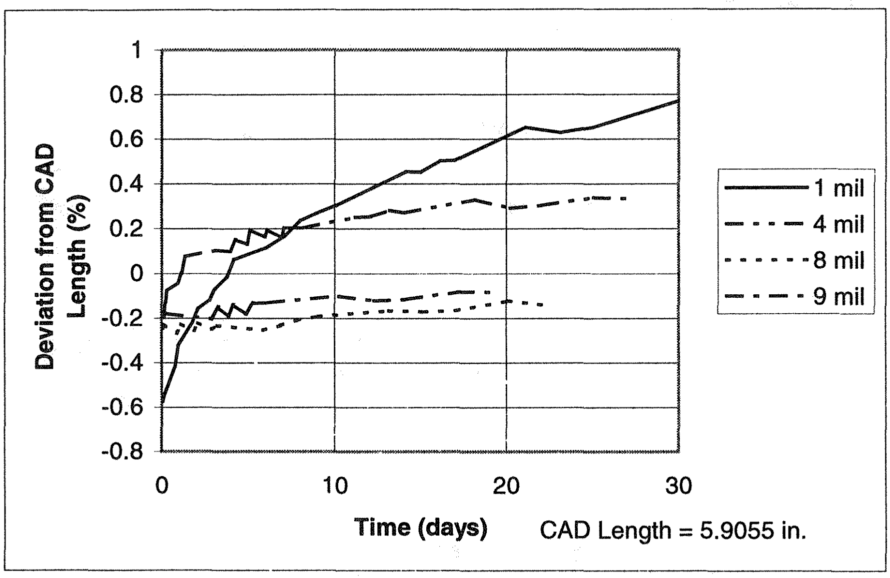

Figure 3: Dimensional Behavior with Different Hatch Over-cures for Somos® 8100 Green Tensile Bars at Ambient Conditions

Environmental Effects and Dimensional Stability

The effect of the environment after the parts were imaged, cleaned and post-cured was determined on a set of 6 inch tensile bars that had been kept at ambient conditions for about a month. Three sets of six bars made from either Somos® 7110 or Somos® 8110 were sanded lightly, especially on the down-facing surfaces, to remove any remaining supports so that they would be suitable for repetitive weighing. Each set of bars was then left in a large glass jar either at ambient lab temperature (21°C) and humidity, immersed in distilled water, or at 0 % relative humidity (RH). At the start and approximately every five days after that each bar was weighed and the length measured.

The bars made from Somos® 7110 and held at 0 % RH lost an average of 0.003 % weight per day, but their weight was stabilizing. The bars at ambient conditions (Air) actually gained weight slightly presumably due to a slightly increasing humidity in the laboratory with the onset of summer. The bars in water gained a total of 1.2 % weight over 47 days (an average of 0.03 % Wt per day) and had not yet reached equilibrium (Figure 4).

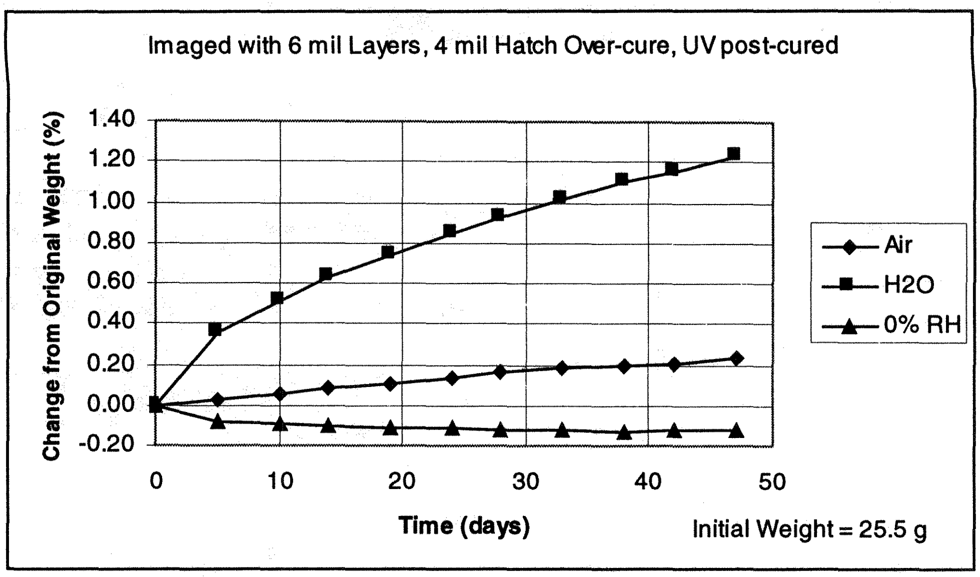

Figure 4: Weight change with Time for Somos® 7110 Tensile Bars at 21°C

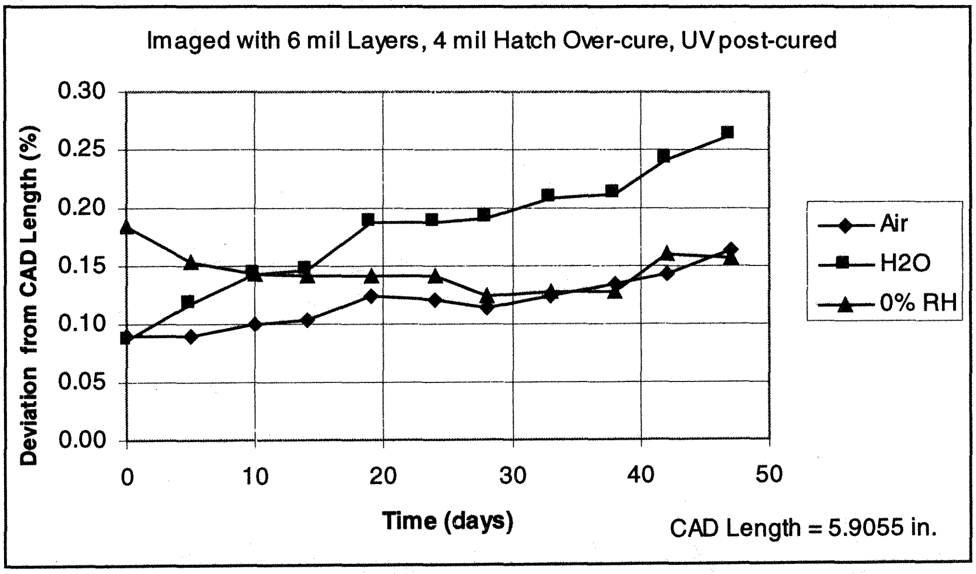

Figure 5: Change in Length with Time for Somos® 7110 Tensile Bars at 21°C

The overall effect on the length of the Somos® 7110 bars was very similar to the weight change (Figure 5). The bars at 0 % RH lost length throughout the study, but then seemed to gain some at the end. The length of the bars at ambient conditions (Air) varied slightly presumably due to varying humidity in the laboratory. The bars in water gained a total of 0.2 % length over 47 days (an average of 0.004 % per day) but had not yet reached equilibrium.

The bars made from Somos® 8110 and held at 0 % RH lost an average of 0.006 % weight per day, but their weight was stabilizing. The bars at ambient conditions (Air) actually gained weight slightly presumably due to a slightly increasing humidity in the laboratory with the onset of summer. The bars in water gained a total of 2.4 % weight over 48 days (an average of 0.05 Wt % per day) but had not yet reached equilibrium (Figure 6).

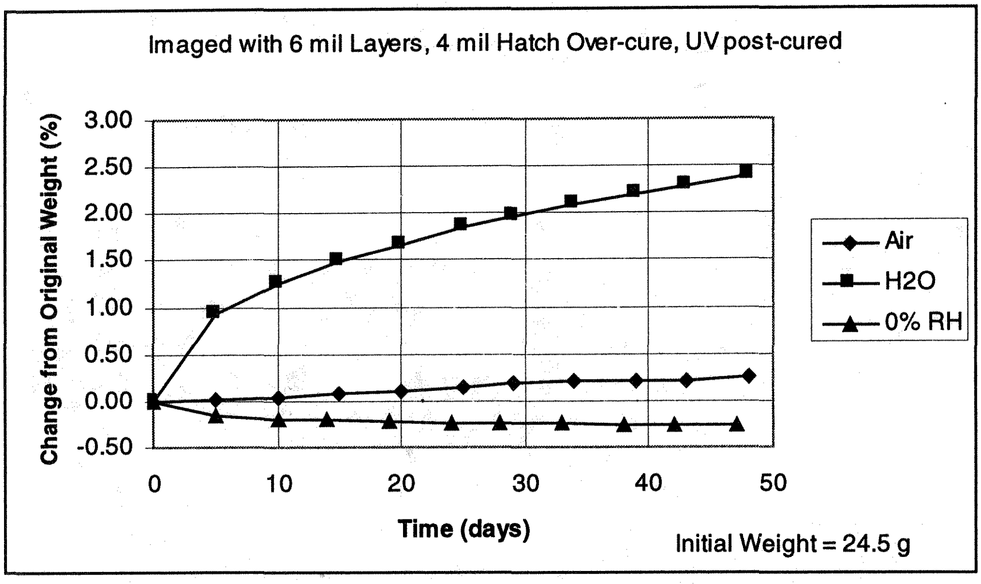

Figure 6: Weight change with Time for Somos® 8110 Tensile Bars at 21°C

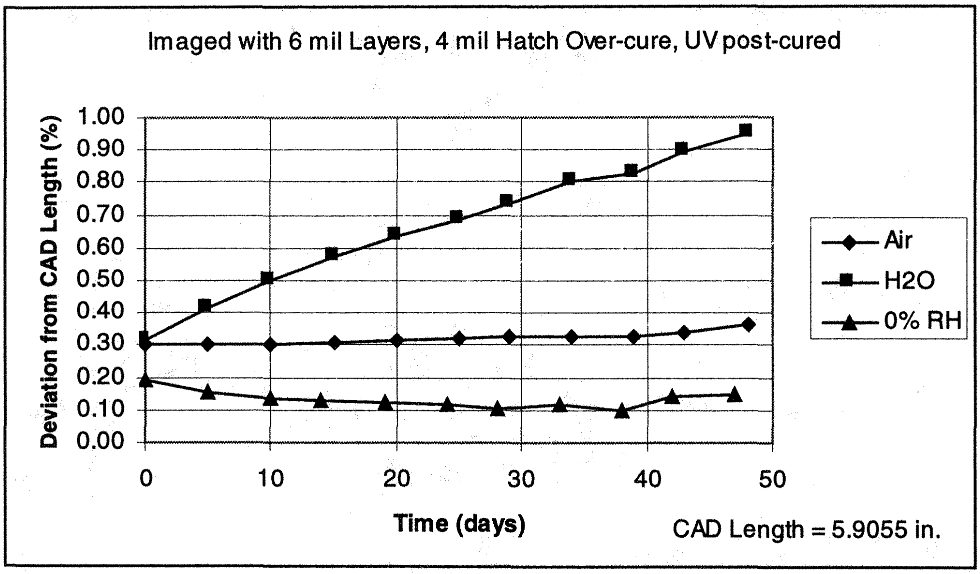

Figure 7: Change in Length with Time for Somos® 8110 Tensile Bars at 21°C

The overall effect on the length of the bars was very similar to the weight change (Figure 7). The bars at 0 % RH lost length throughout the study, but then gained some at the end. The length of the bars at ambient conditions (Air) varied slightly presumably due to varying humidity in the laboratory. The bars in water gained a total of 0.6 % length over 48 days (an average of 0.013 Wt % per day) but had not yet reached equilibrium even after that length of time.

Conclusions

To build dimensionally accurate parts by stereolithography, machine calibration is a very important consideration that should not be overlooked. A way of measuring the imaging accuracy before building parts has been proposed.

It has been shown that the random noise component of the stereolithography process can be a significant contributor to the overall part accuracy. As more attention is given to the individual components that affect dimensional change and therefore random noise, the achievable accuracy levels will improve.

The amount of exposure used during the part build affects the dimensional stability of the part after building. In general, higher exposure provides more stable parts, whether they remain in the green state or if they are post-cured with UV radiation in the conventional way.
This has been shown to be the case with Somos® 8100, one member of a family of stereolithography resins that produce flexible, high impact strength parts. The effect of exposure on other stereolithography resins will be the subject of future studies.

After parts have been built and post-cured it has been shown that environmental conditions, in particular humidity, have a pronounced effect on the dimensional stability. This occurred for parts made from both of the stereolithography resins tested, namely Somos® 7110 (a general purpose, high strength, high heat deflection temperature resin) and Somos® 8110, although the later resin changed the most. For six-inch tensile bars in some environments, equilibration had not occurred over a 47-day period. It was shown that parts left at ambient room conditions are susceptible to dimensional changes due to humidity changes . Further studies are underway to look into these issues at a greater depth and will be reported in the future.

References

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2. Tom Mueller, "A Model to Predict Tolerances in Parts Molded in Pattern Based Alternative Tooling" presented at the Rapid Prototyping and Manufacturing Conference, May 19-21, 1998.
3. Edward G. Gargiulo and Suresh S. Jayanthi, "Current State of Accuracy in Stereolithography" presented at the Measurements and Standards Issues in Rapid Prototyping Symposium organized by NIST, October 16-17, 1997.

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