Process planning to build Mask Projection Stereolithography parts with accurate vertical dimensions

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Abstract

Mask Projection Stereolithography (MPSLA) is a high resolution manufacturing process that builds parts layer by layer in a photopolymer. In this paper, we formulate a process planning method to cure MPSLA parts with accurate vertical dimensions. To this effect, we have formulated and validated the "Layer cure" model that models the thickness of a cured layer as a transient phenomenon, in which, the thickness of the layer being cured increases continuously throughout the duration of exposure. We have shown that for longer durations of exposures, such as those common with MPSLA systems, cure depth varies linearly with exposure. We have also quantified the effect of diffusion of radicals on the cure depth when discrete exposure doses, as opposed to a single continuous exposure dose, are used to cure layers.

Using this work, we have formulated and validated the "Print through" model that computes the extra curing that would occur when multiple layers are cured over each other. We have implemented the Print through model to simulate the profile of a down facing surface of a test part and validated the simulation result by building the test part on our MPSLA system.

1. Introduction

Mask Projection Stereolithography (MPSLA) is an additive fabrication process used to build physical components out of a photopolymer resin. The CAD model of the part to be built is sliced by horizontal planes and the slices are stored as bitmaps. These bitmaps are displayed on a dynamic mask and are imaged onto the photopolymer resin surface. When a bitmap is imaged onto the resin surface, a layer corresponding to the shape of the bitmap gets cured. This layer is coated with a fresh layer of resin by lowering it inside a vat holding the resin and the next layer is cured on top of it. By curing layers one over the other, the entire part is built. This technology has been demonstrated in various papers, like Bertsch et al., (1997), Chatwin, (1998), Monneret et al., (1999), Limaye and Rosen, (2004). The schematic of the MPSLA system realized at Georgia Tech. is shown in Figure 1. The specifications of the system are presented in Table 1.

Print through errors in vertical dimensions of MPSLA part are caused due to residual radiation penetrating to the bottom surface of a MPSLA build, causing unwanted polymerization. In Limaye and Rosen, (2006), the Compensation zone (CZ) approach is proposed as a method to avoid Print through errors. This approach entails subtracting a tailored volume from underneath the CAD model of the part to be built to compensate for Print through. The threshold model of resin cure states that curing occurs if and only if the exposure received is greater than the threshold exposure of polymerization (E_c) (Jacobs, 1992). The idea behind the CZ approach is to control the energy supplied at every point in the resin in such a way at the bottom surface of the desired part will receive an exposure exactly equal to E_c.

In Section 2 analytical models are presented that enable the computation of energy received by any point in the resin as a part is being built. In Section 3, these analytical models

are used to simulate the down facing surface's profile of a MPSLA build. Using this model, the process parameters that can accurately cure a part with a linear down facing surface are obtained.
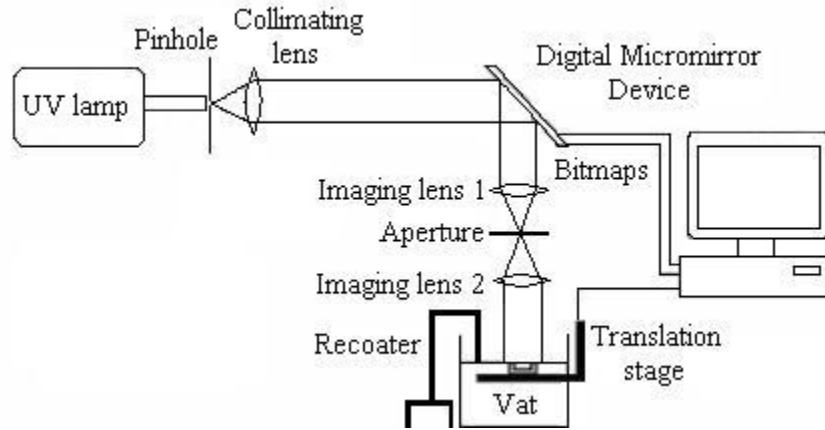

Figure 1 Schematic of the MPSLA system developed at Georgia Institute of Technology

Table 1 Specifications of the Mask Projection SLA system at Georgia Tech

Component	Description	Model/Manufacturer
Broadband UV lamp	Broadband Mercury vapor lamp. Peak at 365nm. 3000mW at 365nm.	ADAC System Cure Spot 50/ Dymax Corporation
Aperture 1	Adjusted to 4mm diameter	Thorlabs Catalog # SMO5D5
Collimating lens	Fused silica Plano convex lens Effective focal length = 40mm Diameter = 25.4mm Radius of surface 1 = 18.4mm Radius of surface 2 = infinity (plane) Lens thickness = 7.1mm Material refractive index = 1.460	Thorlabs Catalog # LA4306-UV
DMD	1024 X 768 array of micromirrors Dimension of micromirror = 12.65µm square. Spacing between mirrors = 1µm	Texas Instruments. Distributed by Prodsys Inc.
Imaging Lens 1 and Imaging Lens 2	Fused silica Plano convex lens Effective focal length = 40mm Diameter = 25.4mm Radius of surface 1 = 35.7mm Radius of surface 2 = 35.7mm Lens thickness = 6.7mm Material refractive index = 1.460	Thorlabs Catalog # LB4030
Aperture 2	Adjusted to 1.5mm diameter	Thorlabs Catalog # SM05D5
Translation stage	XYZ translation stage; 100nm resolution	Applied Scientific Instruments Model # MS2000
Photopolymer resin	E_c, D_p determined experimentally	DSM SOMOS 10120

2. Analytical modeling

In this section, the exposure that any point in resin would receive as a part is being built is modeled. In Section 2.1, the curing of a layer is modeled as a transient phenomenon. In Section 2.2, the assumption of the additive nature of exposure is questioned and the effect of time on the diffusion of reactive species is modeled. In Section 2.3, the print through that would occur when multiple layers are cured over each other is modeled.

2.1 Layer cure model

The cure model presented in standard Stereolithography texts, like Jacobs (1992), is fairly simple. It assumes that the depth of cure is proportional to the logarithm of exposure and assumes the threshold model of resin cure. Suppose that irradiance H is incident on the resin surface for a duration t. It would supply an exposure $E = H \cdot t$. This energy would get attenuated as it enters the resin, according to the Beer Lambert's law. The exposure at a depth z is given by $E_z = E \exp(-z / D_p)$. Curing occurs at all points where exposure is greater than or equal to E_c. The thickness of the layer cured will thus be given by equation (1).

$$C_d = D_p \ln(H \cdot t / E_c) \tag{1}$$

where D_p is the depth of penetration of the resin (a measure of attenuation of radiation) and

E_c is the threshold exposure for polymerization.

This model assumes that the attenuation of radiation through a cured layer is the same as that through uncured resin, given by the parameter D_p. We have observed experimentally that the attenuation through a cured layer is significantly less than that through the liquid resin. Thus, the depth of penetration for a cured layer D_{pS} is expected to be different from that for the liquid resin D_{pL}. We model the effect of this different attenuation by modeling the layer curing as a transient phenomenon.

Suppose irradiation H is incident on the resin surface at a particular location. It will initiate curing after time t_c (let us call it as "critical time"), when the exposure received by the resin equals E_c.

$$t_c = \frac{E_c}{H} \tag{2}$$

A thin film of cured resin shall be formed at the surface. The energy now incident will have to pass through this film of cured resin and then, through the uncured resin under the film.

Suppose that, as shown in Figure 2, the thickness of the film cured after time t is equal to z. The exposure at the bottom surface of this film is equal to E_c. At time $t+dt$, the next dose of energy equal to $H \cdot dt$ is incident on the top of the layer. This energy gets attenuated following the Beer Lambert's law of attenuation as it passes through the cured layer of thickness z and the energy reaching its bottom surface is $H \cdot dt \exp(-z / D_{pS})$. Here, it adds up with E_c, the energy already at the bottom of the film and causes an incremental curing equal to dz. This incremental curing is given by

$$dz = D_{pL} \ln[\frac{H \cdot dt \exp(-z / D_{pS}) + E_c}{E_c}] \tag{3}$$

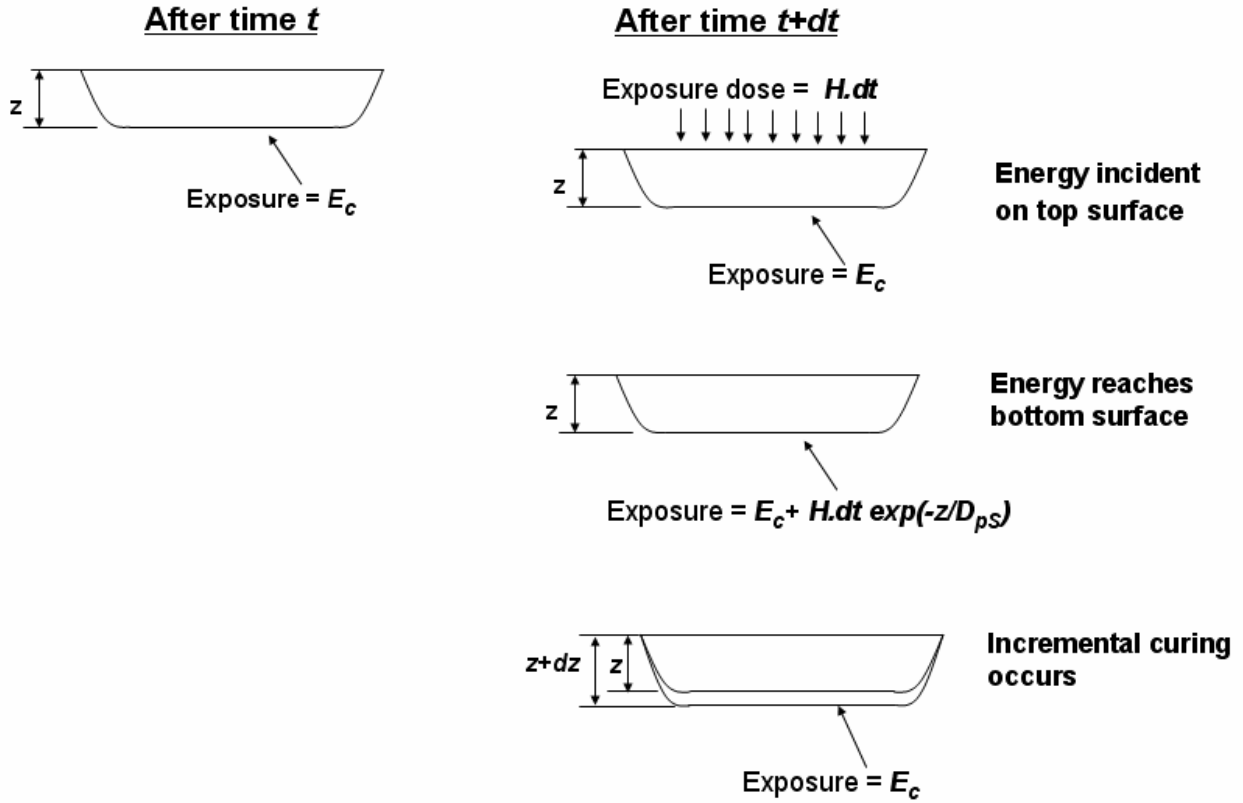This is a first order differential equation with the initial condition: $z = 0$ at $t = t_c$.

Figure 2 Modeling layer curing as a transient phenomenon

We solve equation (3) numerically to obtain the relationship between the depth of cure (z) and the time of exposure (t). We found that the solution to equation (3) converges when the time domain was discretized into steps of 0.1s, i.e. when $dt = 0.1$.

In equation (3), the parameters D_{pL}, D_{pS} and E_c are to be determined experimentally. In order to determine these parameters, the experimental procedure as shown in Figure 3 was adopted. An optical window was placed in contact with the free surface of resin contained in a vat and lines were imaged onto the resin for various time durations. The thicknesses of the cured lines, sticking to the optical window, were measured and plotted against the time that they were imaged. Equation (3) was integrated numerically, by discretizing the time domain into durations of 0.1s. The analytical and experimental results agreed the best when the values of the unknown parameters were chosen to be:

$D_{pL} = 0.192$mm

$D_{pS} \rightarrow$ infinity

$E_c = 10.2$ mJ/cm^2

From Table 2, it can be seen that the experimental and analytical values of cure depths agree very well. The value of the depth of penetration through liquid resin (D_p) and that of the threshold exposure of polymerization (E_c) are specified by the manufacturer to be 0.16mm and 9.8mJ/cm^2 respectively. These values agree very closely with the values that we have measured. It should be noted that the value of depth of penetration through cured resin (D_{pS}) tends to infinity, indicating that a cured layer is almost transparent to radiation.
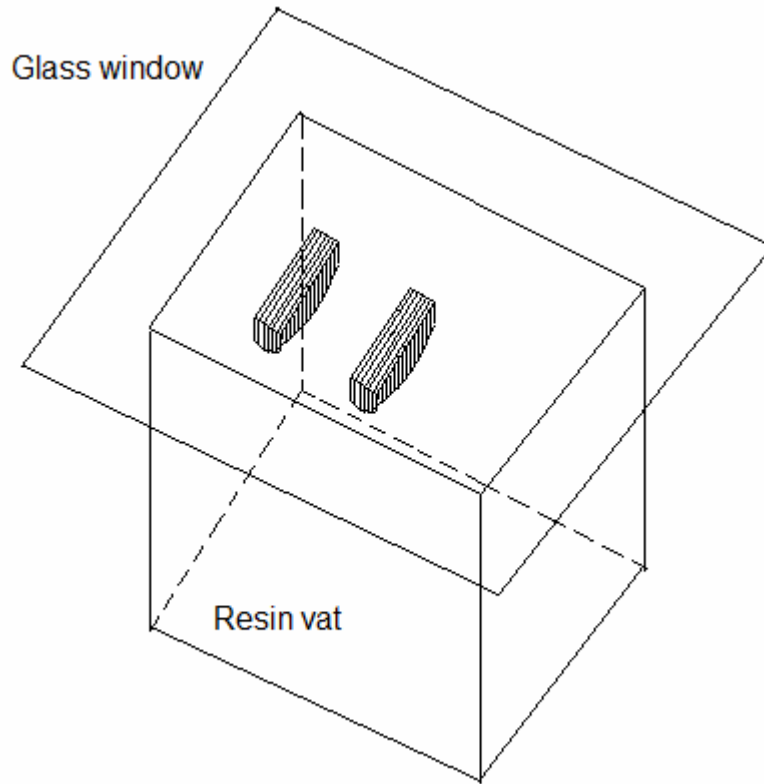
Figure 3 Characterizing the photopolymer

Table 2 Analytically computed and experimentally measured values of layer thicknesses

Time of exposure (s)	Exposure (mW/cm^2)	Analytical value of layer thickness (μm)	Experimental value of layer thickness(μm)
15	10.5	0	0
20	14	53.76	68.26
25	17.5	126.34	136.52
30	21	198.92	204.77
35	24.5	279.57	273.03
40	28	354.84	341.29
45	31.5	413.97	409.55
50	35	473.12	477.81

The thicknesses of the lines cured on our system have been plotted against the time of exposure in Figure 4. It is seen that the plot can be best approximated by a straight line, which indicates that the relationship between the thickness of a cured layer and the time of exposure is linear. The relationship is given in equation 4.

$$z = 19.172.E - 195.59 \tag{4}$$

It should be noted here that Hadipoespito et al, (2003) had characterized the same photopolymer (DSM SOMOS 10120) using their Mask Projection Stereolithography system and had also observed a linear relationship between cure depth and time of exposure.
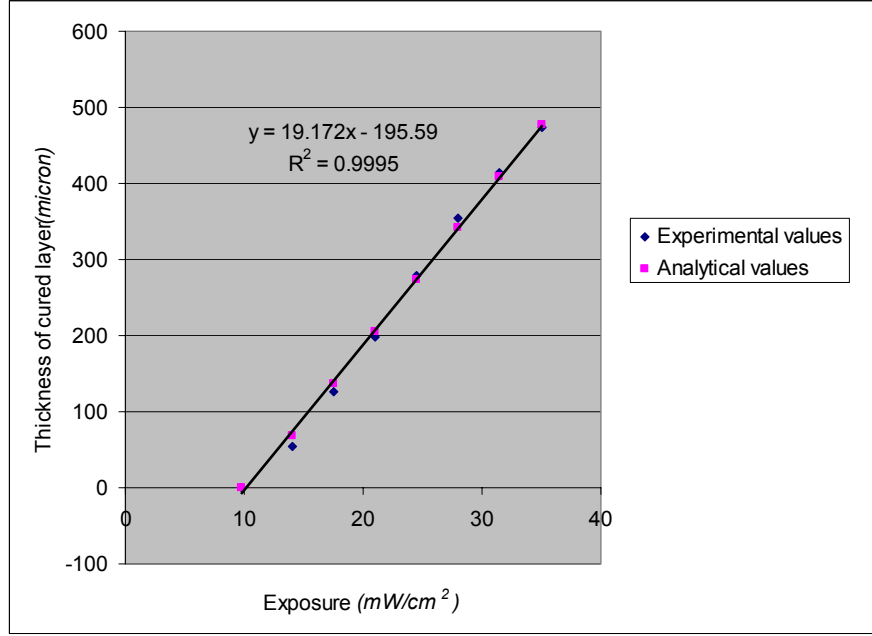
Figure 4 Thickness of layer cured plotted cured against exposure

In general, we postulate that the working curve for a Stereolithography resin used with a Mask Projection Stereolithography system is linear, of the form

$$z = A \cdot (E - E_c) \tag{5}$$

where A is the slope of the working curve, which is the rate at which the cure-front propagates into the resin depth, and

E_c is the threshold exposure of polymerization.

For our system,

$A = 19.172$ μm/(mW/cm^2), or 1.9172mm^3/mW and

$E_c = 10.2$ mW/cm^2

2.2 Radical diffusion model

Jacobs (1992) assumes exposure to be additive. It means that if a particular location in the depth of resin receives multiple doses of exposures, their effect is the same as if that exposure was continuous. We have experimentally found that the additive nature of exposure is a strong function of time.

Suppose a radiance H is incident on the resin surface for a time duration t_1 and causes curing up to a depth z. This cured layer is allowed to remain floating on the resin for a time t. Now, the top surface of the cured layer is exposed to the same radiance H for a second time interval of duration t_2. This second dose of energy will pass through the transparent layer and will add up with the exposure at the bottom surface. The assumption of additive exposure assumes that the exposure at the bottom surface will be equal to

$$E_b = E_c + (H \cdot t_2) \exp(-z / D_{pS}) \tag{6}$$

Since $D_{pS} \rightarrow \infty$,

$$E_b = E_c + H \cdot t_2 \tag{7}$$

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This exposure will cause further incremental curing underneath the already cured layer.

In reality there will be a diffusion of the reactive species underneath the cured layer when it sits in the resin vat for the duration of time t. These excited reactive species will carry away with them energy equal to $k.E_c$. This will reduce the effective exposure underneath the cured layer to $(1-k)E_c$. Thus, after the second exposure dose, the exposure at the bottom surface will be less than that calculated in equation (7), and will be equal to

$$E_b = (1-k)E_c + H \cdot t_2 \tag{8}$$

The value of 'k' (let us call it as "Radical diffusion factor") in equation (8) is found to be a strong function of time. As a result of the diffusion of radical species, the incremental curing will not start the moment the second exposure reaches the bottom surface, but only after the energy carried away by the diffusing radicals is compensated for. Thus, curing starts only after a time t' where

$$t' = \frac{kE_c}{H} \tag{9}$$

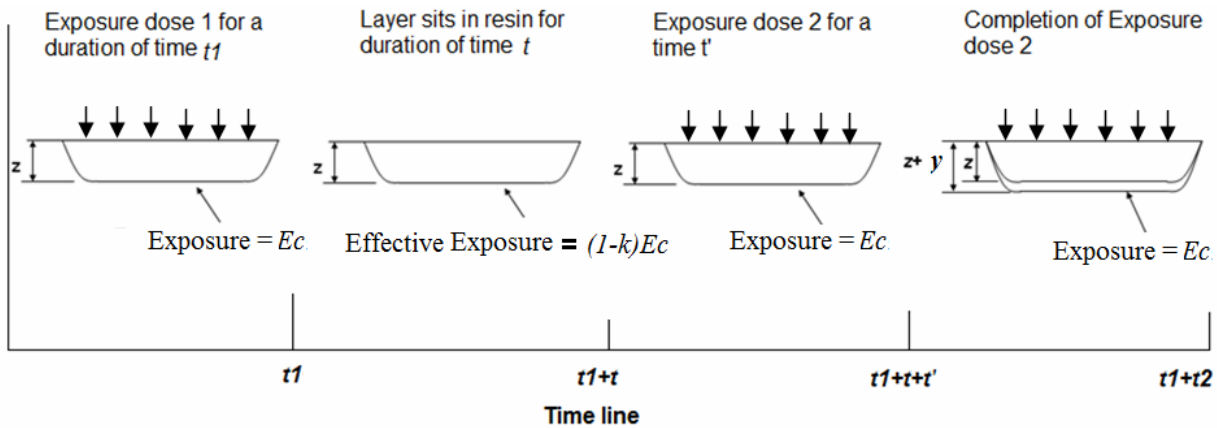This phenomenon is illustrated in Figure 5.

Figure 5 Effect of two discrete exposures on the thickness of a layer cured

Thus, the plot of cured depth against time of exposure, as presented in Figure 4, will be modified if the exposure is not continuous. It will be as shown in Figure 6. The portion of the plot parallel to the time axis is the time it takes for the second exposure dose to compensate for the energy lost along with the diffusing radicals.
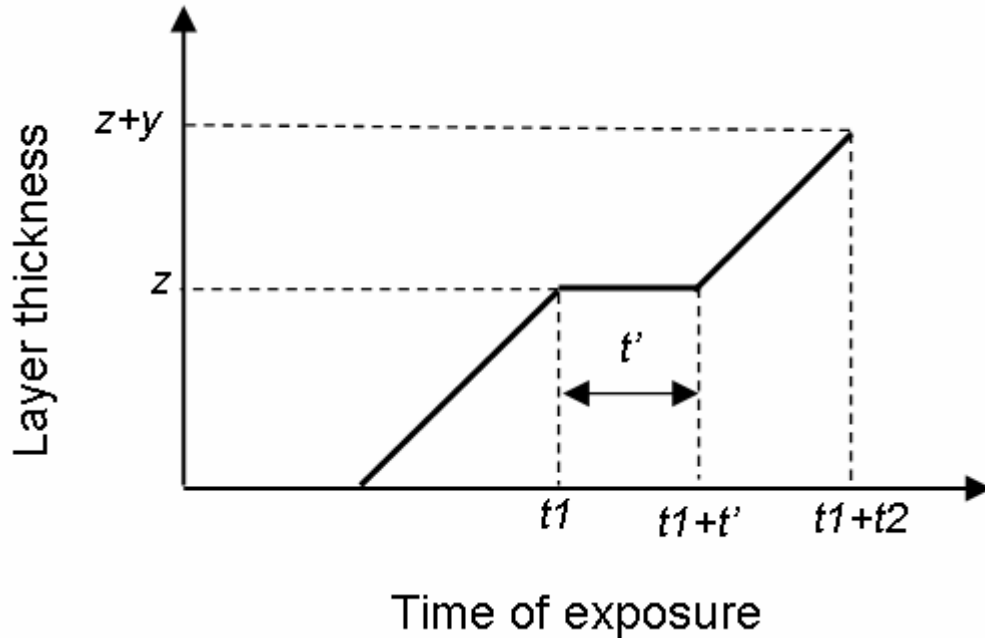
Figure 6 Effect of diffusion of radicals underneath a cured layer on the layer thickness

Measuring the value of *k*

The value of k is measured experimentally as follows. The same arrangement as shown in Figure 3 is done, with a glass window kept flush with the free surface of resin held in a vat. A single layer is cured for a time t_1 seconds. This layer is allowed to remain in the vat for various durations of time (t seconds) and then, the same line is exposed onto the window for a duration 25s. The thickness of the line cured is measured. The value of t', which will give the best agreement with the thickness of the cured line is obtained experimentally. The plots are shown in Figure 7.
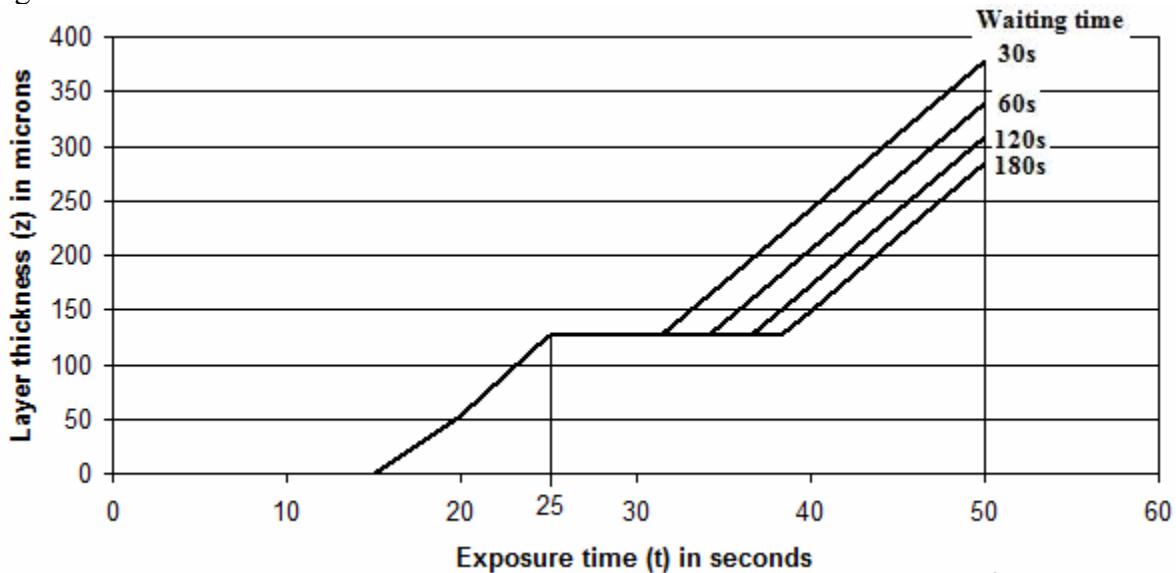

Figure 7 Experimentally determining the value of *t'* for various waiting times

The value of t', and hence, that of k is tabulated against the time that the layer is allowed to sit in resin (t) before receiving the second dose of exposure, in Table 3. A logarithmic curve is fitted to the data, as shown in Figure 8. The relation between the radical diffusion factor and the time allowed for diffusion is given by equation 9.

Table 3 Effect of time on the diffusion of radicals underneath a cured layer

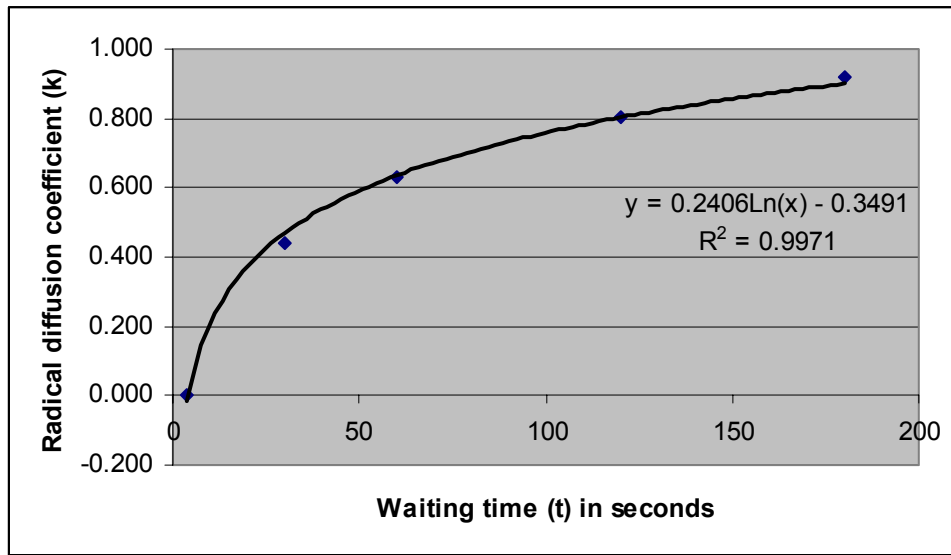| Time allowed for diffusion (s)	Time required to compensate for diffusion of reactive species (t') in seconds	Diffusion factor (k)
4	0	0
30	6.4	0.439
60	9.2	0.631
120	11.7	0.803
180	13.4	0.920

Figure 8 Plot of the radical diffusion factor against the waiting time

$$k = 0.2406\ln(t) - 0.3491$$

The general form of equation relating the radical diffusion factor and time allowed for diffusion is

$$k = B\ln(t) - C \tag{10}$$

where B and C are constants that will depend upon the resin, the temperature of resin and even the size of the vat.

Thus, the energy at a cure front sitting in a resin vat for t seconds will be given by

$$E_t = (1-k)E_c$$
$$E_t = [1 + C - B\ln(t)] \cdot E_c \tag{11}$$

2.3 Modeling print through

Based upon the Layer cure model and the Radical diffusion model developed in Sections 2.1 and 2.2, it is possible to model the print-through that would occur when a multi-layer part is cured. Suppose that an n layered part, as shown in Figure 9 is built. Let radiance H be incident on

the layers. Let the thickness of the kth layer be given by LT_k. and the exposure supplied to cure it be given by E_k. Suppose the time allowed for the resin to settle before exposing the kth layer is t_k seconds.
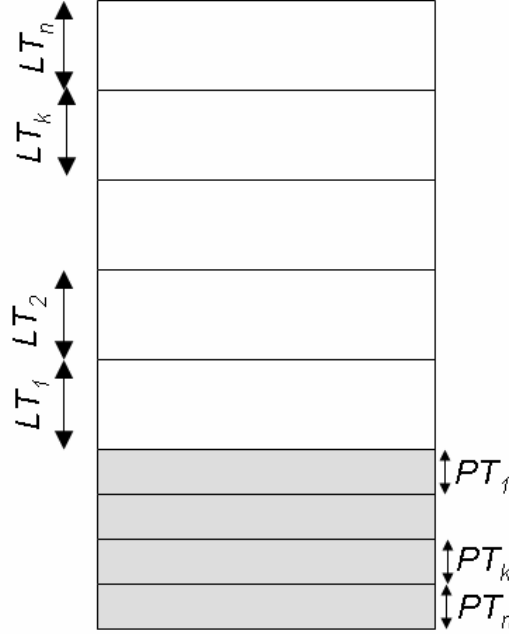

Figure 9 Modeling the print through occurring in a "n" layered part

We now model PT_k: the print through that would occur because of radiation penetrating from the kth layer. From equation 5, we can find that an exposure equal to $(LT_k / A) + E_c$ is sufficient to cure the layer to the cure depth LT_k. The exposure in excess of this value will penetrate down, un-attenuated, through all the cured layers underneath the kth layer and will cause print-through. Let us denote this exposure as E_{PTk}. It is given by equation 12.

$$E_{PTk} = E_k - (LT_k / A) - E_c \qquad (12)$$

This energy will add to the energy already existing at the bottom surface. The energy at the bottom surface, after the $(k-1)^{th}$ layer is cured, will be equal to the threshold exposure of polymerization E_c. The diffusion of radicals would have occurred at the bottom surface for a time t_{dk}, given as the summation of the time that was allowed for the resin to settle before exposing the kth layer, and the time that it took for the kth layer to be cured.

$$t_{dk} = t_k + [(LT_k / A) + E_c]/H \qquad (13)$$

After the diffusion of reactive species that would occur during the time t_{dk}, we can compute the effective exposure at the bottom surface by applying equation (11),

$$E_b = [1 + C - B \ln(t_{dk})]E_c \qquad (14)$$

The print-through will be caused by exposure E_{bk} at the bottom surface, given as the addition of the exposures given by equations 12 and 14.

$$E_{bk} = E_k - (LT_k / A) - E_c + [1 + C - B \ln(t_{dk})]E_c \qquad (15)$$

Simplifying,

$$E_{bk} = E_k - (LT_k / A) + [C - B \ln(t_{dk})]E_c$$

The print through caused by this exposure can easily be derived from equation 5 as

$$PT_k = A(E_{bk} - E_c) \qquad (16)$$

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$$PT_k = A\{E_k - (LT_k / A) + [C - B\ln(t_{dk}) - 1]E_c\} \tag{17}$$

The total print through will be equal to

$$PT = \sum_{k=1}^{n} PT_k \tag{18}$$

The total height of the part cured will thereby be equal to

$$h = \sum_{k=1}^{n} LT_k + \sum_{k=1}^{n} PT_k \tag{19}$$
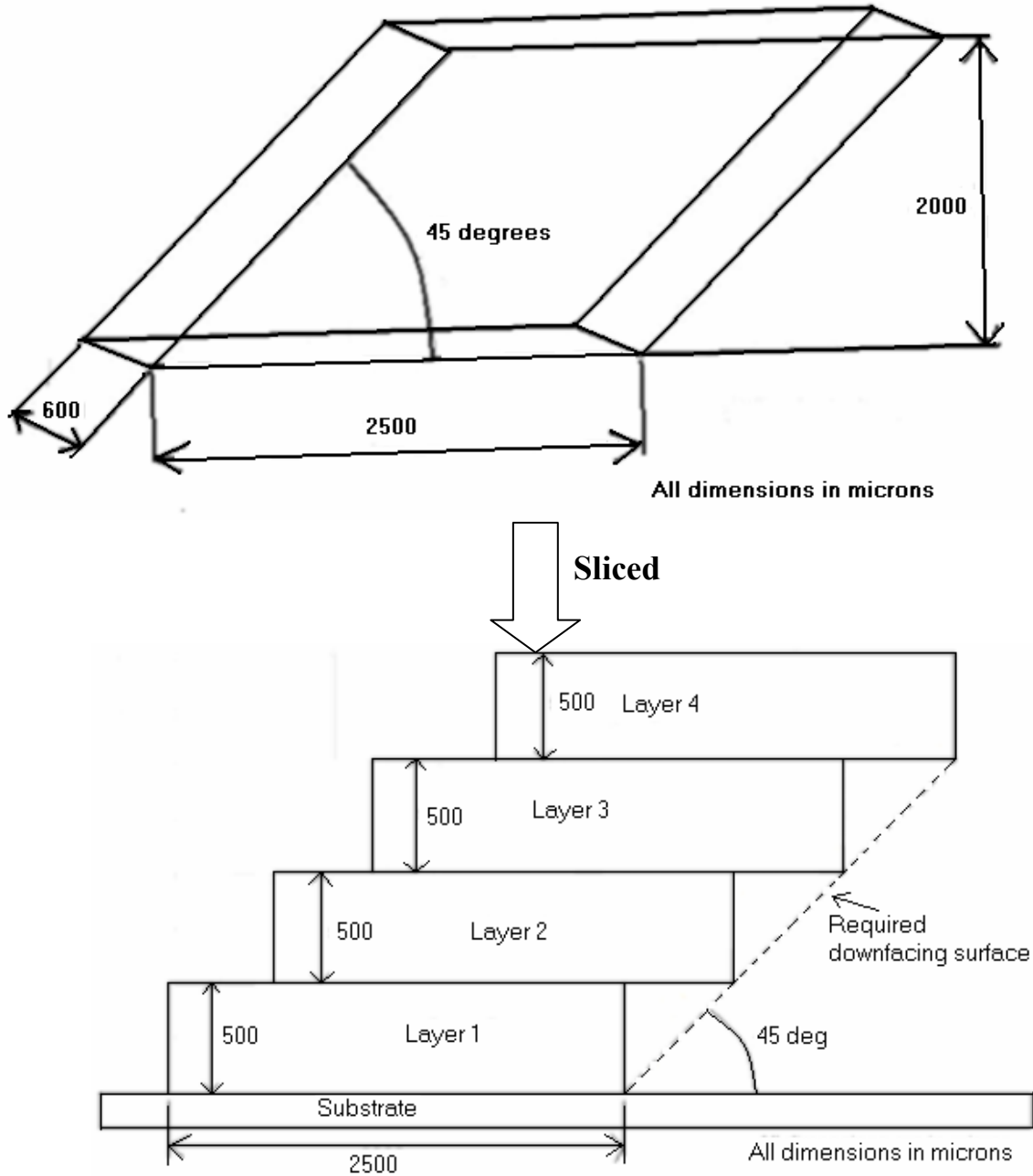
3. Simulating the down facing profile of a part

Figure 10 Test part to simulate the down facing profile of a MPSLA build

In this section, we use the print through model developed in Section 2.3 to simulate a test part. This part is validated by building the part on our MPSLA system. The part shown in Figure 10 was built. The part consists of four layers, each 2500μmX600μm and 500μm thick. Every layer was alike and was built by imaging the same bitmap on the resin surface for the same time of exposure (80s). We found that 80s of exposure time is required for the layers to bind to each other. The layers were built offset by 500μm by translating the platform laterally under the imaging system.

Using the Irradiance model developed in Limaye and Rosen (2007), we generated the irradiance distribution on the resin surface when the bitmap is imaged onto it. This gave us the irradiance (H) at every lateral location on the resin surface. The time allowed for the resin to settle before exposing any layer was 60s, i.e. $t_k = 60s$. The value of print through at every lateral location on the built part was computed using equation 17 and the down facing surface was simulated as shown in Figure 11.
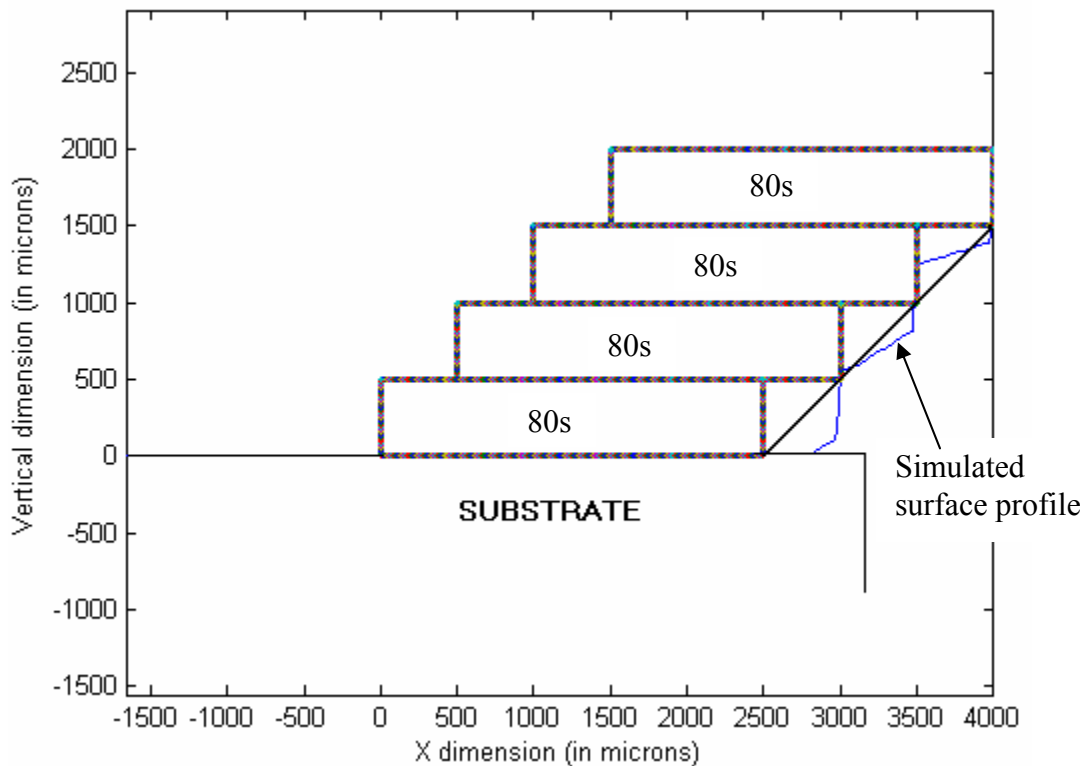

Figure 11 Simulating profile of the down facing surface for every layer exposed for 80s

The four layered part was built on our system using the same parameters as that used in the simulation. The part's profile, as shown in Figure 12, can be seen to be qualitatively agreeing with the simulated profile. In Figures 11 and 12, rectangles are shown corresponding to the layers that would have been cured had there been no print through and no irradiance variation across a cured layer. The ideal down facing surface is shown by the line at 45^0 is shown in Figures 11 and 12. It is seen in both the figures that there is extra curing.
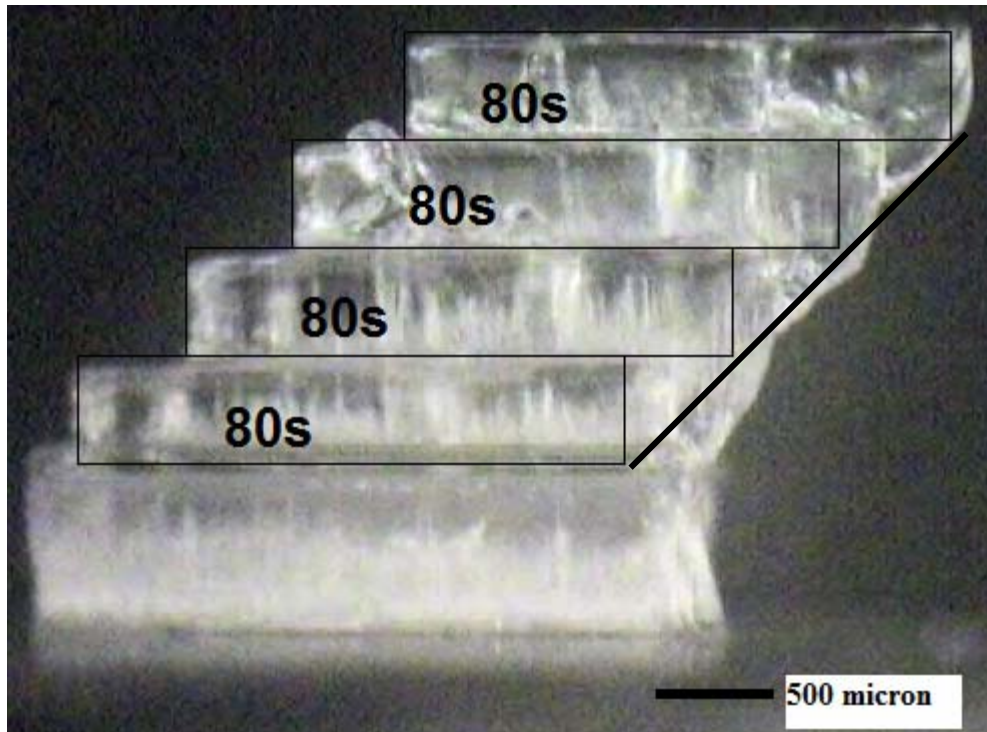
Figure 12 Profile of experimentally cured part with every layer exposed for 80s

It should be noted that the cured part is smoother than the simulated part. We surmise that it is because of partially gelled resin occupying the nooks of the stair steps.

A better agreement with the down facing surface can be obtained by implementing the Compensation zone approach. The overhanging portions under the lower three layers should be exposed for lesser durations. By simulating the down facing profiles for various combinations of exposure times for the overhanging portions on the layers, we obtained a part profile that agreed the best with the ideal down facing surface as shown in Figure 13. The times of exposures for the overhanging portions of the layers, from the bottom-most to the top most, were input to the simulation as 32s, 60s, 65s and 82s respectively. A test part with these times of exposures was cured on our MPSLA system. The profile of the cured part, as shown in Figure 14, gives a much better approximation to the required linear down facing surface.

4. Closure

In implementing the Compensation zone approach, we have formulated two fundamental new theories: the Transient model of layer curing and the Radical diffusion model. The simulated part's down facing profile and the experimentally cured part profile agree only qualitatively. The Compensation zone approach has been demonstrated by demonstrating an improvement in curing a desired linear down facing surface on a test part. We believe that a better agreement can be obtained by standardizing the characterizing the part cleaning process. Also, the threshold model of resin cure, which assumes that curing occurs at any resin location if and only if the exposure at that location exceeds the threshold exposure of polymerization, needs to be investigated. With this work, the Compensation zone approach can be implemented with an even higher fidelity.
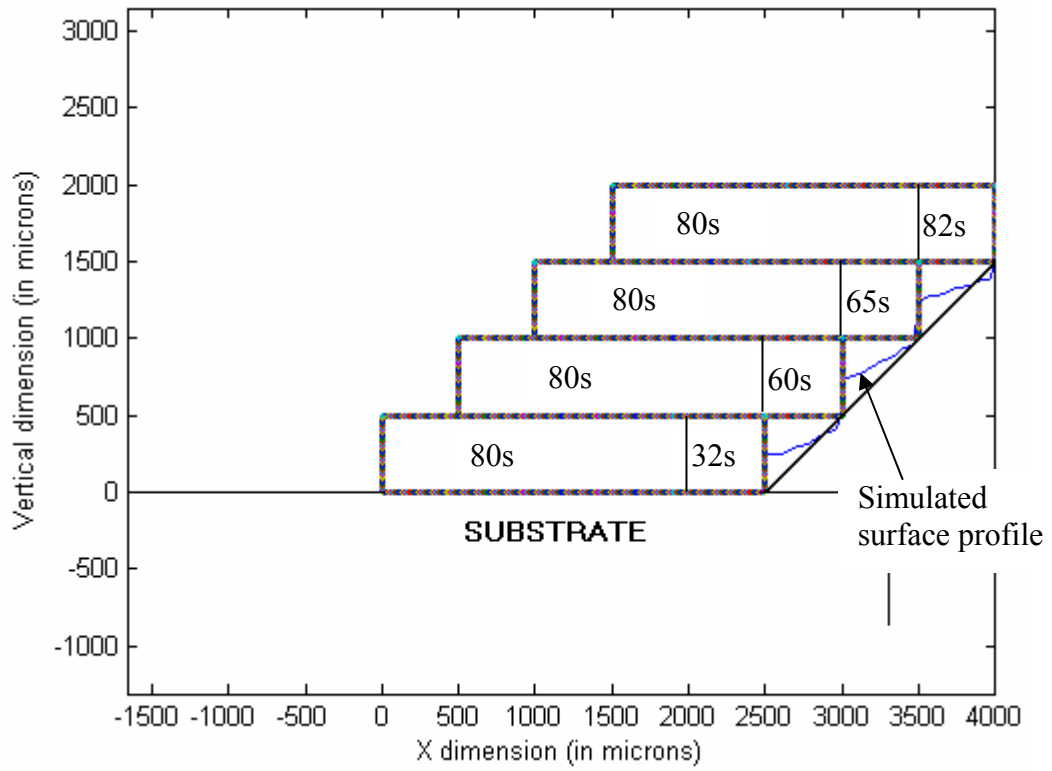
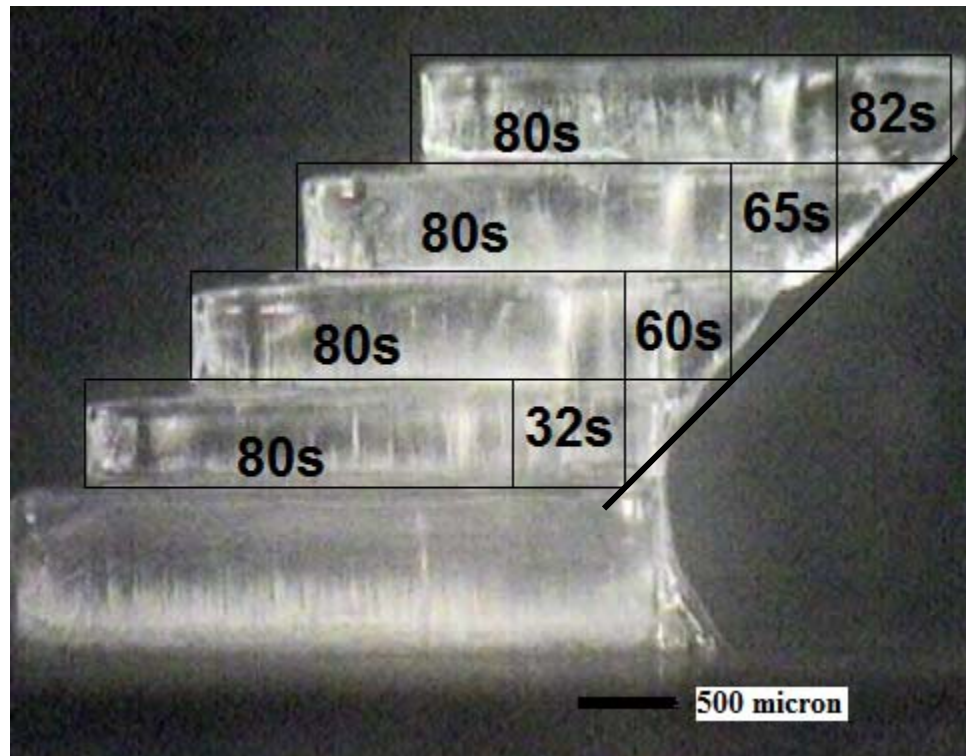**Figure 13 Simulation of down facing surface of part built with Compensation zone approach**

Figure 14 Profile of experimentally cured part with Compensation zone approach

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