USE OF PARAMETER ESTIMATION FOR STEREOLITHOGRAPHY SURFACE FINISH IMPROVEMENT

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ABSTRACT

In order to improve Stereolithography (SLA) surface finish, a systematic approach based on estimation of process parameters is needed. In this paper, the exposure on a desired SLA build surface is formulated as a function of process parameters. The deviation of exposure on this surface from the critical exposure, which is the threshold that determines curing in the SLA process, is formulated using least squares minimization. By applying inverse design techniques, SLA process parameters that satisfy this least squares minimization are determined. Application of parameter estimation formulation to important SLA geometries is presented and the results, including surface finish improvement, are discussed.

1. INTRODUCTION AND MOTIVATION FOR STUDY

Stereolithography (SLA) is a layered rapid prototyping process in which an UltraViolet (UV) laser is used to selectively cure a vat of liquid photopolymer resin in order to physically fabricate a part from a CAD model. With the growing interest in applying this technology to the microfabrication area comes the need to improve the surface finish of SLA process.

SLA surface finish is determined by the combination of cure shapes, which result from individual laser scans. Each laser beam scan generates a three dimensional cured volume called a voxel. The size and shape of a voxel is determined by not only process parameters such as laser beam power, irradiance profile, scan speed, laser beam angle with resin surface, but also the resin constants such as critical exposure and depth of penetration. Since the surface finish is dependent on the voxels, by changing the process parameters on the fly, it is possible to change and improve the surface finish of SLA parts.

Commercial SLA machines do not give the user the freedom to change build parameters in order to improve surface finish. In particular, the coupled relationship between laser beam location and angle made with resin surface has limited the ability to improve surface finish for downfacing parts, where it has been shown that the angle between the laser beam and the intended build surface influences the surface finish of a part. Moreover, generating better upfacing surface finish is possible by changing the angle of the build surface while keeping the laser stationary (Reeves and Cobb 1997; Lu, Fuh et al. 2001). The typical variation of surface roughness with respect to this angle for upfacing surfaces is presented in Figure 1.
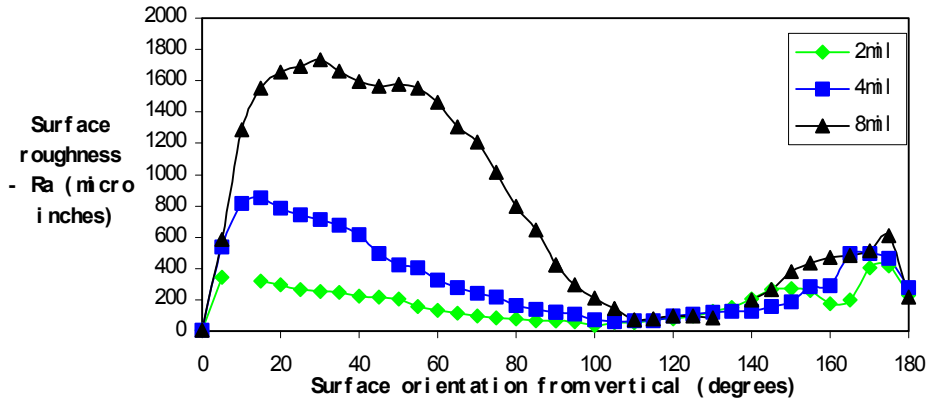
Figure 1. Cusp height versus build orientation (Sambu 2001) (Reeves and Cobb 1997).

In Figure 1, the variation of surface roughness with respect to surface orientation is given for the SLA 250 machine. When θ is small (between 0 and 15 degrees), the angle between the laser beam and vertical is large but surface roughness is very small, which means better surface finish.

Since a stationary vertical laser beam is used in the commercial SLA machines, stair steps limit the surface finish of final parts. In Figure 2, the resulting cured outline of a downfacing quadratic surface is shown.
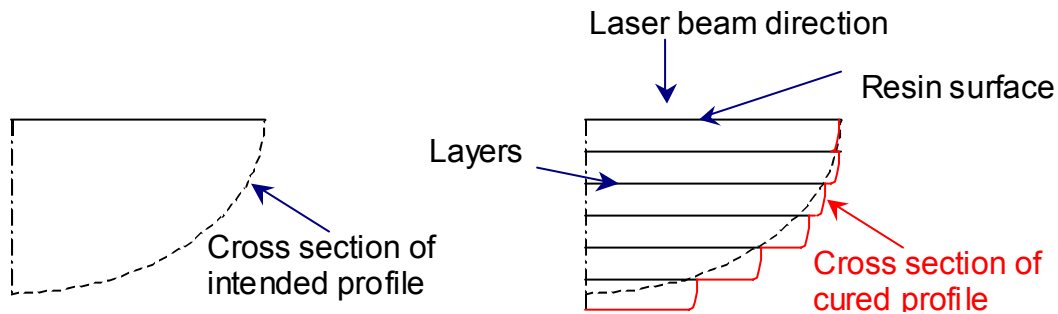

Figure 2. Difference between intended and cured profiles.

Previously, an analytical cure model based on the irradiance profile, scan parameters, and machine configuration of commercial SLA machines was developed (Sager and Rosen 2005). Using this model, we have demonstrated the ability to capture the slanted cure shapes that result when the laser beam in the SLA process is not vertical (Sager and Rosen 2004) at corners of the vat of commercial SLA machines. In addition, the size and shape of cure profiles can be predicted using this analytical model.
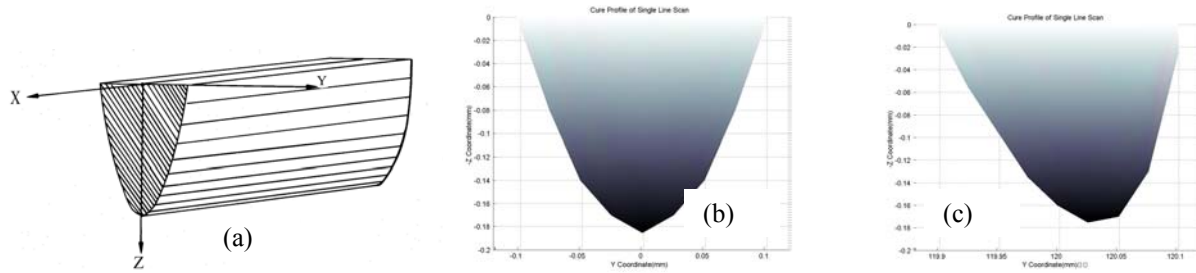
Figure 3. Parabolic cross-section of a voxel: (a) along scan direction x (b) with vertical laser beam (c) with slanted laser beam.

The ability to predict cure shapes accurately presents the opportunity to do SLA process planning with more degrees of freedom. Commercial SLA machines have fixed power and limited ability to change scan speeds within a layer. By decoupling laser beam position and angle made with the resin surface, it is possible to generate angled voxels. By enabling direct control of laser beam angle, different cure profiles can be obtained. Cure profiles with varying sizes and shapes can then be used to improve the surface finish of an SLA part feature via better surface approximation (Kataria and Rosen 2000). Even though no commercial SLA machines with active laser beam angle control exist, we believe that such machines can be designed. Therefore, what is needed is a systematic approach to estimate process parameters based on the SLA shape that is to be built. This could be achieved by SLA process parameter estimation.

Parameter estimation is the name given to a class of engineering problems where observations that make up some set of data are used to estimate the parameters that constitute a mathematical model (Aster, Borchers et al. 2005). In the SLA process, exposure is the parameter that determines whether a point is solidified within the vat. Therefore, exposure becomes the focus of the SLA parameter estimation formulation.

2. SLA EXPOSURE AND CURE MODELING

At the center of SLA exposure and cure modeling is the irradiance profile of the laser beam used in the process. Irradiance is the radiant power of the laser per unit area (mW/cm^2), and is often denoted by H (x, y, z). For the purposes of this study, the laser beam irradiance profile is considered to have Gaussian distribution. The exposure at a point in the vat is obtained by integrating the irradiance over time, given as:

$$E(x,y,z) = \int_{t_{start}}^{t_{end}} H[x(t), y(t), z(t)]dt \qquad \text{(Equation 1)}$$

where the Cartesian coordinates are defined as in Figure 3a.

In the SLA process, the critical exposure, E_c, is taken as a meaningful threshold above which a point is solidified. Therefore, the points in the vat which have an exposure value equal to that of the exposure define the cured profile outline. Even though the threshold model has limitations, its accuracy depends on the irradiance values involved in the process. For irradiance values above 40 mW/cm^2, the threshold model is accurate for approximating resin behavior (Slopek 2005). In the SLA process, irradiance values around the center of the laser beam are typically far

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greater than 40 mW/cm^2 (in excess of 100,000 mW/cm2). Therefore the exposure threshold model is an accurate approximation for the purposes of this study.

Using the Gaussian nature of the laser beam, the formula for exposure at a point in the vat can be obtained. For a straight line scanned along the x axis in Figure 3a with a constant irradiance profile, the exposure at the distance (y, z) away from the scan line in the vat is given as:

$$E(y,z) = \sqrt{\frac{2}{\pi}} \left(\frac{P_L}{w_o V} \right) e^{\left(\frac{-2y^2}{w_o^2} \right)} e^{\left(\frac{-z}{D_p} \right)} \quad \text{(Jacobs 1992)} \qquad \text{(Equation 2)}$$

where P_L is the laser power, w_o is the beam waist radius, V is the scan speed, and D_p is the depth of penetration. In Equation 2, the quantity y is the perpendicular distance between the scan line and the point of interest in the vat. The z quantity in Equation 2 is the perpendicular distance between the point of interest in the vat and the resin surface.

During the SLA process, the exposure value resulting from each laser beam scan is calculated using Equation 2. Since exposure is assumed to be an additive quantity, the individual exposure values resulting from several laser beam scans are summed to obtain the final exposure value for a point in the vat. It should be pointed out that for non-constant irradiance profiles, Equation 1 needs to be numerically integrated. Since this paper is a first step in SLA parameter estimation formulation, Equation 2, which is the simplified case of SLA exposure calculation, will be used.

3. SLA PARAMETER ESTIMATION FORMULATION

As aforementioned, the critical exposure value is the resin constant that determines the extent of the cured profile. Therefore, the outline of the surface of interest in the SLA parameter estimation formulation can be expressed as a grid along which the exposure value will be equal to the critical exposure. By specifying the shape and length of this grid, we can effectively control the surface finish of the cured outline. For the points on this grid, the goal is to minimize the deviation of the exposure received from the critical exposure, as shown in Figure 4.
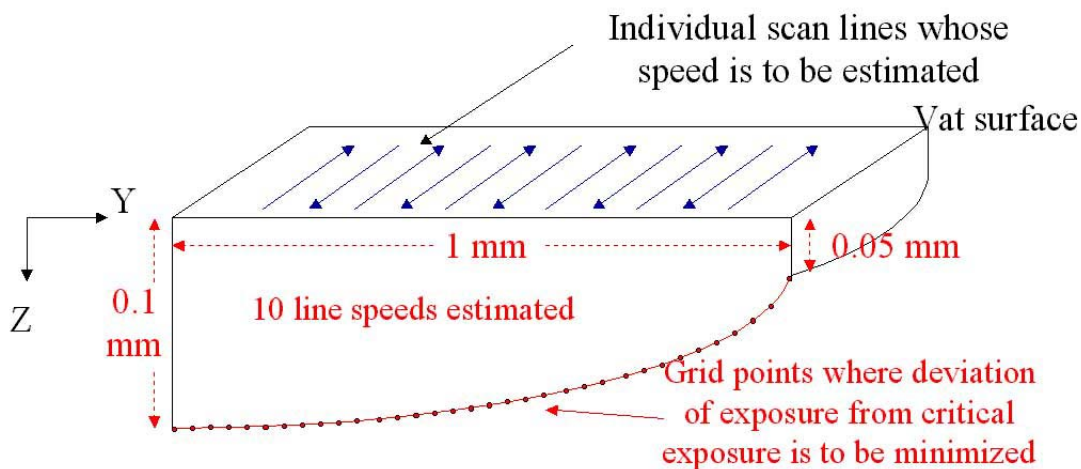

Figure 4. SLA parameter estimation formulation example.

In Figure 4, the cross-section of the SLA part cure profile is shown. This profile has an outline between 0.05 mm and 0.1 mm that is defined by quadratic curve and is 1mm long. The surface we are interested in is the downfacing surface, which has a quadratic shape. In this formulation, we try to minimize the deviation of the exposure at each grid point from critical exposure. Since points are cured as a result of laser beam scans, the goal is to estimate the scan speed for each line that will satisfy the least squares minimization. To achieve this, the laser power, the beam waist, and the spacing between each laser beam scan are kept constant. By using the predetermined number of scan lines, the scan speed for each line that will give the desired outline is estimated using the parameter estimation formulation.

There are a number of techniques to solve parameter estimation formulations. In the SLA process, several hundred laser beam scans are used to fabricate a three dimensional part. Even though the formulation presented here is relatively simple, for more complicated formulations involving several layers with many scans per layer, the parameter estimation problem could become unstable. In addition, due to the nonlinear nature of the problem, the problem formulation could become ill-conditioned. For such problems, the Levenberg-Marquardt method is a suitable and powerful solution technique (Özisik and Orlande 2000). Therefore, for solving the SLA parameter estimation problem, the Levenberg-Marquardt method was chosen. The general procedure for solving the SLA problem is as follows:

Step 1. Determine the values for SLA laser constants of laser power and beam waist, process variables of number of layers, number of scan lines, hatch spacing between scan lines, layer thickness, and resin constants E_c and D_p. In addition, choose a positive scalar value for the damping parameter (μ^k) for first iteration μ^0 such as 0.001 and define the tolerance value ε that will be used for iterations.

Step 2. Estimate the initial scanning speed vector V for all scan lines.

Step 3. Calculate the y and z coordinates of all the grid points on the surface of interest.

For each iteration k = 0, 1, ….k
Step 4. Calculate the sum of the squares error or objective function for the initial formulation by:

$$S(V^k) = \sum_{i=1}^{I} \left[E_{c_i} - E_i(V^k) \right]^2 \qquad \text{(Equation 3)}$$

where S = sum of squares error or objective function

$E_i(V) \equiv$ exposure at grid point i

E_{c_i} = critical exposure at grid point i

N = total number of scans = total number of unknown parameters (since we have 1 parameter to estimate per scan line)
V = Scan speed parameter to be estimated
I = number of grid points

Step 5. Compute the sensitivity matrix J and the diagonal matrix Ω by:

$$J(V^k) = \left[\frac{\partial E_i^T(V)}{\partial V}\right]^T = \begin{bmatrix} \dfrac{\partial E_1}{\partial V_1} & \dfrac{\partial E_1}{\partial V_2} & \dfrac{\partial E_1}{\partial V_3} & \cdots & \dfrac{\partial E_1}{\partial V_N} \\[2mm] \dfrac{\partial E_2}{\partial V_1} & \dfrac{\partial E_2}{\partial V_2} & \dfrac{\partial E_2}{\partial V_3} & \cdots & \dfrac{\partial E_2}{\partial V_N} \\[2mm] \vdots & \vdots & \vdots & & \vdots \\[2mm] \dfrac{\partial E_I}{\partial V_1} & \dfrac{\partial E_I}{\partial V_2} & \dfrac{\partial E_I}{\partial V_3} & \cdots & \dfrac{\partial E_I}{\partial V_N} \end{bmatrix}$$
(Equation 4)

where $\dfrac{\partial E_i}{\partial V} = -\sqrt{\dfrac{2}{\pi}}\left(\dfrac{P_L}{w_o V^2}\right) e^{\left(\frac{-2y^2}{w_o^2}\right)} e^{\left(\frac{-z}{D_p}\right)}$ (Equation 5)

$$\Omega^k = diag\left[\left(J^k\right)^T J^k\right]$$ (Equation 6)

Step 6. Solve the following linear system of algebraic equations, obtained from the iterative procedure of the Levenberg-Marquardt method (Özisik and Orlande 2000):
$$\left[\left(J^k\right)^T J^k + \mu^k \Omega^k\right]\Delta V^k = \left(J^k\right)^T\left[E_{c_i} - E_i\left(V^k\right)\right]$$ (Equation 7)

Step 7. Then compute the new estimate for vector V^{k+1}:
$$V^{k+1} = V^k + \Delta P^k$$ (Equation 8)

Step 8. Solve the Exposure problem with the new estimate V^{k+1} in order to find $E_i\left(V^{k+1}\right)$. Then compute $S(V^{k+1})$ as in Step 4.

Step 9. If $S(V^{k+1}) \geq S(V^k)$, replace μ^k by $10\mu^k$ and return to Step 6.

Step 10. If $S(V^{k+1}) < S(V^k)$, accept the new estimate V^{k+1} and replace μ^k by $0.1\mu^k$.

Step 11. Check the predetermined stopping criterion. In this formulation, the stopping criterion, which is defined by $\left\|V^{k+1} - V^k\right\| < \varepsilon$, is 1 x 10^{-7}. If the stopping criterion is satisfied, stop the iterative procedure. Otherwise, replace k by k+1 and return to Step 5.

It should be noted that the Levenberg-Marquardt implementation already exists in MATLAB and has been utilized for SLA parameter estimation. The implementation used in MATLAB uses the nonlinear least squares (lsqnonlin) function, which uses the Levenberg-Marquardt algorithm as its default method. This particular function uses the initial guess for scan speed as the input to calculate the exposure for each iterative step until the stopping criterion is satisfied. The output of this function is the estimated vector for scan speed values.

Since the scan speed is taken as the only parameter to be estimated per scan line in this formulation, calculation of the sensitivity matrix as presented in Step 5 is relatively straightforward. However, it is possible to incorporate more parameters into this calculation.

4. APPLICATION OF PARAMETER ESTIMATION METHOD

Using the method presented above, parameters for important SLA geometries were estimated. Then, these parameters were used to simulate the cure shape based on the developed analytical cure model (Sager and Rosen 2004; Sager and Rosen 2005). Single-layer and multi-layer cross-sections of part geometries were used in the parameter estimation formulation to estimate the speed of laser beam scans in a SLA250/50 machine using DSM Somos 7110 resin, which has an E_c value of 8.2 mJ/cm^2 and a D_p value of 0.14 mm. Nominal laser power and beam waist values of 35 mW and 0.127 mm were used in the formulation. All formulations had 10 lines per layer whose scan speeds had to be estimated. The spacing between the lines was 0.1 mm and the layer thickness was 0.1 mm, which are both nominal values for the SLA process. The overview of the SLA shapes that were used in parameter estimation formulation is shown in Figure 5.
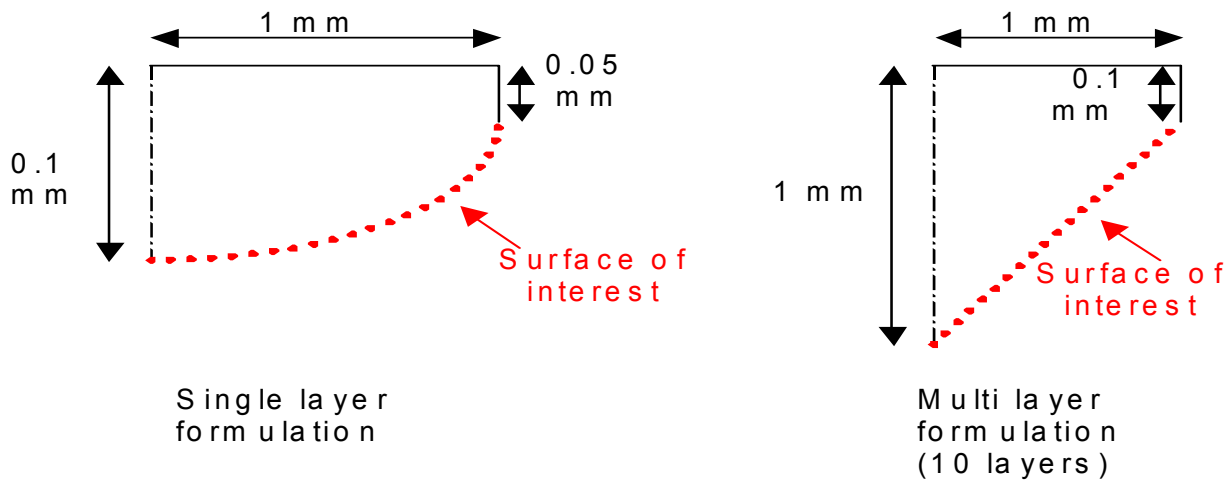

Figure 5. SLA parameter estimation problem formulations (each layer is 0.1 mm thick).

In Figure 5, the problem formulations for the SLA parameter estimation problems are shown. As seen, the single layer formulation had a quadratic downfacing surface whereas the multilayer formulation had a slanted downfacing surface. For both formulations, as indicated in Figure 4, the cross-section that is perpendicular to the laser beam scan direction is shown.

For both formulations, the scan speed values estimated using the SLA parameter estimation algorithm were used to simulate the resulting cure shapes in MATLAB. In addition, .stl files that are identical to the cross-sections presented in Figure 5 were generated and sliced using Lightyear software in order to obtain scan speed information. The goal here, for each formulation, was to compare the cure shape obtained from parameter estimation to the cure shape obtained from actual SLA machine scan parameters.

The single layer formulation had a desired thickness that is very thin (between 0.05 mm and 0.1 mm). In order to cure such a thin cross-section, high scan speed values are needed. Therefore, it was not surprising that the parameter estimation resulted in scan speed values that ranged from 1700 mm/s to 3000 mm/s, which are fast compared to the nominal scan speed of the SLA 250/50 machine (760 mm/s). However, by varying the scan speed for each scan line, a quadratic-shaped cure profile was obtained as shown in Figure 6(a).
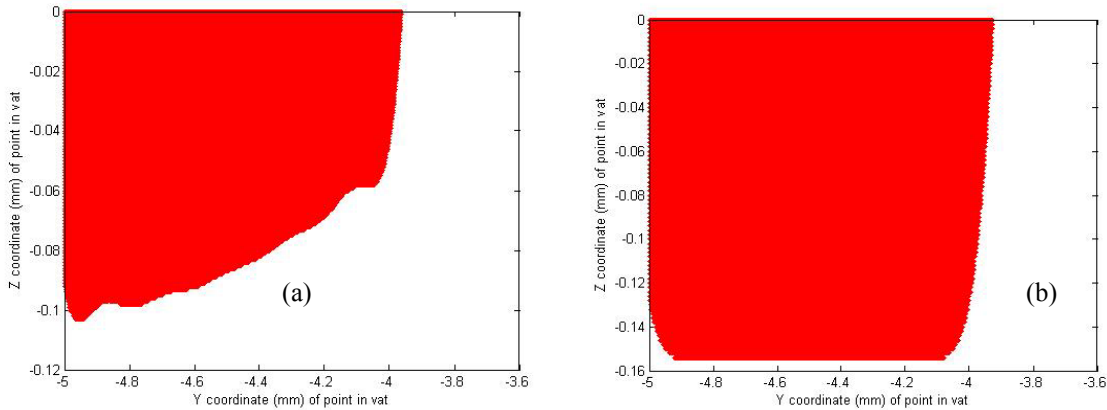

Figure 6. Single layer cure shape comparison. (a) resulting from parameter estimation (b) resulting from commercial SLA machine.

As seen in Figure 6a, the cure shape at the ends of the intended profile is not very accurate. This is an expected result since a limited number of parallel scan lines are used in the formulation. With the estimation of more parameters per scan line and using a different number of scan lines, it is possible to estimate the cure profile end points more accurately. In any case, the profile in Figure 6a matches the intended quadratic surface profile from Figure 5.

On the other hand, the simulated cure profile in Figure 6b does not resemble the intended quadratic cure profile. The profile in Figure 6b was simulated using the estimated scan speed values from the commercial SLA machine slicing software Lightyear. Since the layer thickness in a commercial SLA machine is 0.1 mm thick, the software slices such a thin part as one block, resulting in a uniform scan speed for all the scan lines within that layer. As a result, the estimated scan speed of 1400 mm/s gives a cured profile that is about 0.16 mm thick with a uniform downfacing surface. This example highlights the limitations of the build styles typically used in commercial SLA machines in adapting different scan speeds for different lines within a layer. As a result, layers resemble rectangular blocks, which, when stacked on top of each other as a multilayer build, result in severe stair steps.

For the multilayer SLA parameter estimation problem, 10 layers were used to simulate the desired cross-section whose thickness ranges from 0.1 mm to 1 mm. Similar to the single layer formulation, the multilayer parameters, when used in the simulation, result in a cure profile that resembles the intended cure profile quantitatively and qualitatively. Again, the ends of the cure profile are slightly inaccurate as shown in Figure 7a. The range of estimated scan speed values for this formulation range from 3 mm/s to 2000 mm/s. This range is fairly large, and would be difficult to implement on the fly. However, the upper scan speed values are still within the capability of state of the art galvanometer mirrors, and with careful process planning, could be implemented successfully.

In Figure 7b, the simulated cure profile based on scan speed values obtained from Lightyear software is shown. For this part, the scan speed obtained from Lightyear software was 1125 mm/s. Visibly large peaks and valleys are observed on the surface in Figure **7**b. As aforementioned, this is due to the combination of constant scan speed and vertical laser beam in the commercial SLA machine configuration. The surface finish of the cure profile in Figure 7b is significantly worse than the surface finish of the cure profile in Figure 7a. Furthermore, the cure profile in Figure 7b is 0.1 mm thicker than intended.
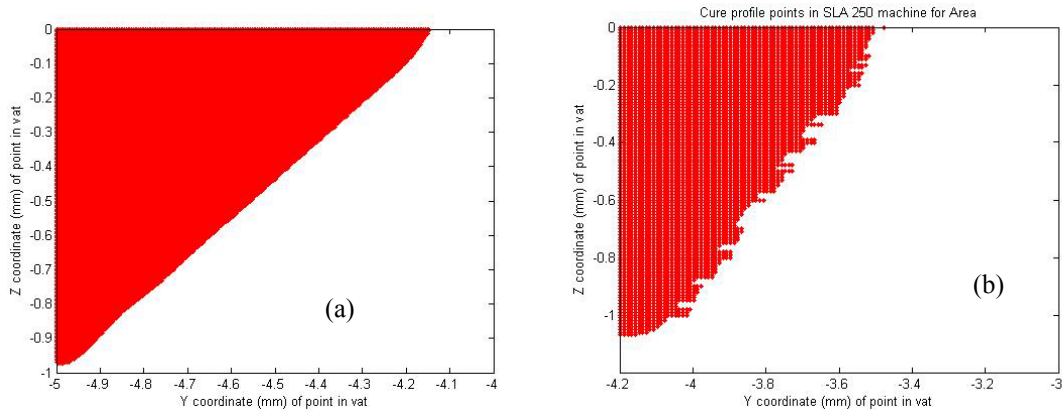

Figure 7. Multilayer cure shape comparison. (a) resulting from parameter estimation (b) resulting from commercial SLA machine.

The multilayer build example highlights how the surface finish could be improved by reducing stair steps in the SLA process. The parameter estimation formulation presented here is a 1-parameter per scan line estimation. When combined with the ability to estimate the angle the laser beam makes with the resin surface for each scan line, the slanted shape of cure profiles could also be taken advantage of. In short, the parameter estimation method could become a very powerful tool to do process planning for challenging surface finish requirements such as optical lenses and microscale devices.

5. CONCLUSIONS AND FUTURE WORK

In this paper, the use of parameter estimation in the SLA process for important SLA geometries has been shown. By estimating the scan speed for laser beam scans, the resulting surface finish of SLA parts has been improved. To our knowledge, this is the first time that parameter estimation and inverse design techniques have been applied in SLA process planning for improving the surface finish.

Even though the formulation used for exposure is simplified using a number of assumptions and only 1 parameter per scan line is estimated, parameter estimation has been demonstrated to be a powerful tool that can be used in process planning. Based on our ongoing work in exposure modeling, more sophisticated parameter estimation problems that will involve dynamic irradiance profiles will be formulated and solved. These problems will involve larger sensitivity matrices where a number of parameters for several layers will be estimated.

Estimated parameters for SLA geometries will be used to generate build files where the scan speed could be varied for a limited number of scan lines. Then, actual SLA parts will be fabricated and measured to validate the results of the parameter estimation problem solutions. In

particular, the surface finish of simulated shapes (such as those in Figures 6a and 7a) and actual SLA parts will be quantified in terms of surface roughness average. By analyzing and comparing the two, the potential of parameter estimation to improve surface finish in the SLA process will be quantified.

By combining parameter estimation in process planning with the ability to fabricate thinner layers at faster speeds, significant improvements in surface finish could be achieved. An example of this is shown in Figure 8.
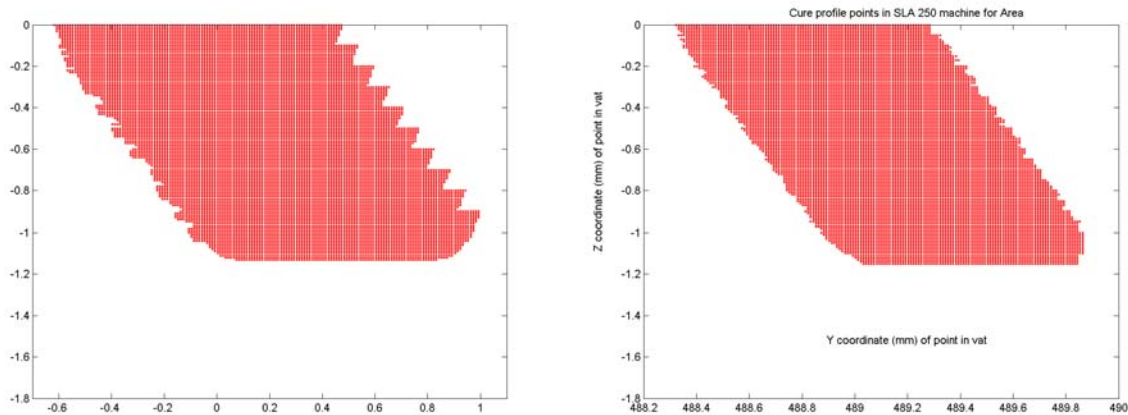

Figure 8. Surface finish improvement by using slanted laser beam.

In Figure 8a, the 10-layer cross-section, which has a 30-degree sidewall, is first scanned with a vertical laser beam. Significant stair steps can be seen on the upfacing surface, where the surface roughness average was measured to be around 8 microns. On the other hand, when the laser beam is parallel to the sidewall at 30 degrees, the stair steps were reduced dramatically and the surface roughness average dropped to 2.4 microns. This is shown in Figure 8b. By incorporating thinner layers and slanted laser beams into SLA process planning and using parameter estimation, significant surface finish improvement could be achieved.

However, it should be kept in mind that the as-built surface finish of SLA parts also depends on other factors for angled surfaces such as layer thickness and viscosity of the resin (both contribute to meniscus smoothing of a surface), which are not estimated as part of this formulation. In addition, the surface finish of the final SLA parts depends on cleaning and post-curing procedures, which are not tackled within the parameter estimation formulation.

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