An Experimental Study of the Parameters Affecting Curl in Parts Created Using Stereolithography

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Abstract:

This paper describes an experimental study of some stereolithography build parameters to determine their effect on curl deformation. The test parts were slabs 2 inches long by 0.375 inch wide and 0.185 inch thick. Parts were imaged with consideration of five parameters: hatch type, layer thickness, hatch spacing, hatch overcure, and fill cure depth However, because of the failure to create viable pieces with certain combinations of the parameter values, statistically significant results were obtained only for a TRIHATCH build with a 0.010 inch layer thickness. Results indicate a primary dependence of curl on hatch spacing with the need to consider combined effects of the parameters.

INTRODUCTION

Stereolithography is a photopolymer solid imaging process for rapid-prototyping and manufacturing that involves scanning a laser beam to sequentially draw or print cross sections of a model on the surface of a photo-curable liquid polymer.[1] With an installed capital investment exceeding $60 million dollars in the United States alone, there is considerable incentive to make full and efficient use of this technology.

One of the most challenging goals of rapid prototyping is the generation of accurate and dimensionally stable parts. The ultimate dimensions of a part built on a layer by layer basis depend on many factors that must be carefully balanced to produced accurate parts. The inability to understand and control the parameters leads to many problems including post-cure shrinkage, swelling, cantilever curl distortion, vertical wall post-cure distortion and horizontal slab distortion [2]. An unfortunate fact of acrylate polymerization is shrinkage and attendant residual stresses which reside in the cured parts. These stresses often result in distortion of the work-piece.[3]

The problem of curl distortion has been discussed by several authors and a number of ways to minimize it have been proposed. Curl may be defined as any out-of-plane deflection of a flat layer and is the result of interlayer shear stresses residual to the solidification process. 3D Systems, Inc., has studied this problem extensively and has developed a diagnostic test to measure curl in terms of the distortion distance and cantilever length. [4] Although models for quantifying the curl parameter have been proposed and various parameters identified, the relative importance of the parameters and a theoretical model for curl distortion still needs to be developed.

The purpose of this study was to experimentally determine the parameters that are most important in minimizing curl and warp deformation. A designed experiment was used to statistically determine the relative importance of the parameters.

THEORY

In the course of preparing a part for stereolithography as many as twenty parameters may have to be selected that will govern the imaging process and the qualities of the final object. Five essential parameters were selected for inclusion in this study:

Layer Thickness,
Hatch Style,
Hatch Cure Depth,
Hatch Spacing, and
Fill Cure Depth.

Three-dimensional objects are "sliced" into series of constant thickness, two-dimensional layers to be printed in solid imaging processes. Layer thicknesses are chosen to balance the need to minimize geometric errors in the build direction caused by the inevitable "contouring" of curved surfaces against the desire to achieve a reasonable build time. A few practitioners regularly build parts with thicknesses as thin as 0.0025 inches, but most select a thickness near 0.010 inches.

Each two-dimensional layer is imaged on the photopolymer surface with a specific hatch style selected by the user. Hatching is used to photopolymerize the liquid in the interior regions of a part. The hatch style affects the sequence and amount of polymer solidification in the part and therefore its physical properties and internal stress distribution. Several hatch styles have been developed for photopolymer solid imaging, but only two will be considered here.

The TRIHATCH style images vectors in three directions (0, 60, and 120 degrees relative to the x-axis) to form equilateral triangles, Figure 1. The vectors are imaged without offsets between layers and with cure depths greater than the layer thickness to assure layer to layer adhesion. Up- and down-facing skin fills trap an amount of liquid in the triangular prisms that are formed. The volume of residual liquid resin is related to the spacing and linewidth of the hatch vectors. TRIHATCH imaging was the first commercialized with acrylate resins and systems with low power and short life He-Cd lasers to provide a fast and efficient imaging process. TRIHATCH imaged parts exhibit low curl, but may suffer from postcure warping and swell distortion.

Weave hatch styles image parallel vectors first in the x-direction, followed by parallel vectors in the y-direction. Hatch spacing is selected to be greater than the cured linewidth so the parallel vectors do not interact. Cure depths may be chosen to be less than or greater than the layer thickness depending on the hatch spacing. The STARWEAVE variation of this style,Figure 2, offsets the vectors in sequential layers (STagger), alternates the order of x and y vector writing (Alternating), and alternately stops the vector imaging short of the opposing borders (Retraction). The cure depth in this hatch style is usually less than the layer thickness. The principal advantages of Weave imaging styles are the elimination of swell and post-cure warp distortions. Curl distortions are not universally improved with these styles

Curl distortion can occur in all rapid-prototyping methods that build parts in successive layers where the solidifying material undergoes shrinkage. This shrinkage causes distortion and internal stresses. [5] Figure 3 shows the sequence of steps leading to curl distortion. When a single layer is first imaged on the liquid surface, it is free to shrink without inducing stresses. However, the second and subsequent layers that are drawn are each bonded to the layer below that has already shrunk. If there is shrinkage of these upper layers after they have become bonded to the layers below, a bending moment is introduced that can cause upward displacement of the unsupported ends of the layer. Curl distortion is typically measured in terms of a curl factor [4] defined as the vertical distortion distance, h, divided by the length of the free layer L.

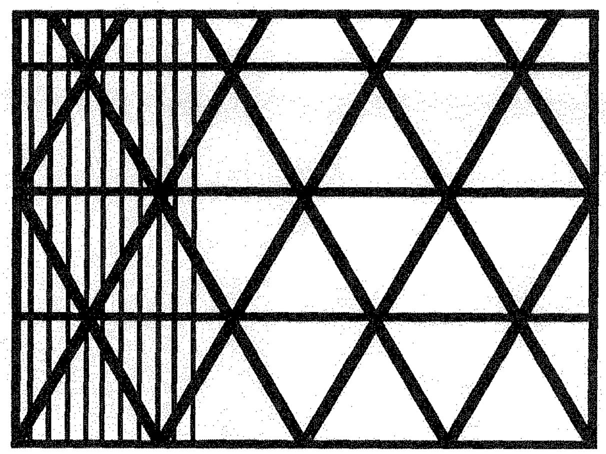

Figure 1: TRIHATCH Imaging Style

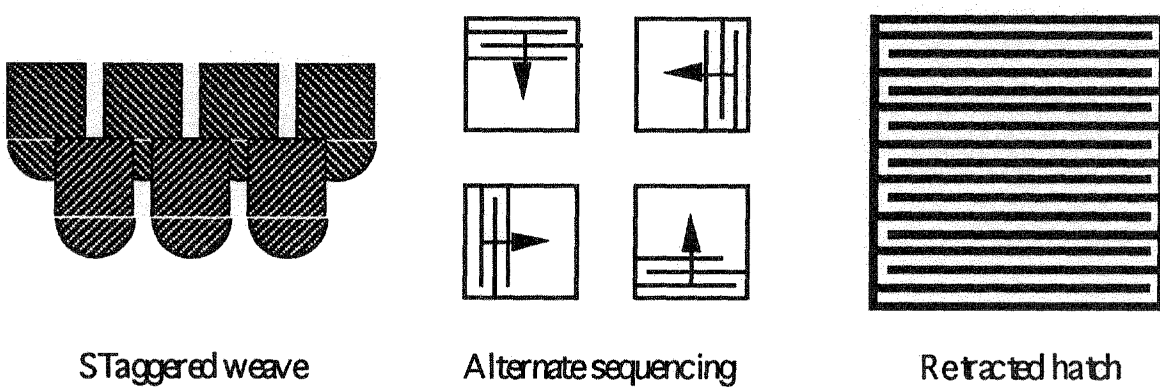

Figure 2: STARWEAVE Imaging Style

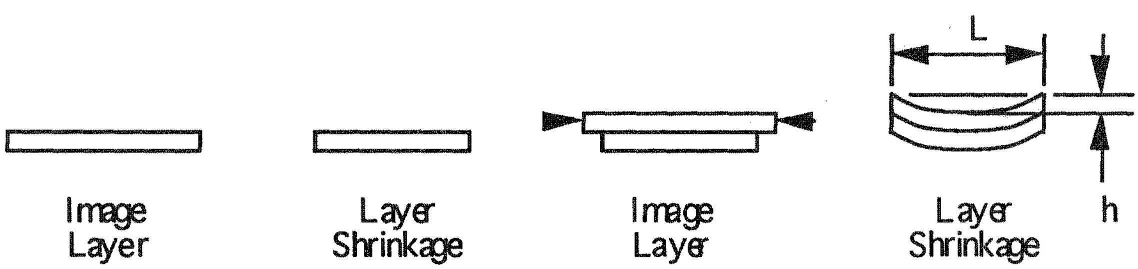

Figure 3: Layer by Layer Build Process

EXPERIMENT

The purpose of our experiment was to statistically determine the relative importance of various build parameters on the curl distortion. The parameters studied were hatch type, layer thickness, hatch spacing, hatch overcure and fill cure depth. The experiment was divided into four sets of parts. Each set consisted of one hatch type and one layer thickness with three different values for each of the three remaining parameters. Thus there were 27 parts for each of the four sets for a total of 108 parts built. Table I summarizes the experiments.

Table I: Ranges of Experimental Parameters

Experiment Number	Hatch Type	Layer Thickness mil	Hatch Spacing mil	Hatch Overcure mil	Fill Cured Depth mil
1	TRIHATCH	10	10,30,50	-2, 2,6	5,15, 25
2	TRIHATCH	5	10,30,50	-2, 2,6	5,15, 25
3	STARWEAVE	10	10,15,20	-2,-1,0	0,12.5,25
4	STARWEAVE	5	10,15,20	-2,-1,0	0,12.5,25

(1 mil = 0.001 inch)

Figure 4 shows the solid model geometry used to create the test pieces. Since the geometry is identical for all the pieces, the curl distortion is proportional to the chord height, h. A dial indicator depth gage was used to measure that height for each experimental piece and that value was recorded as a measure of the curl distortion.

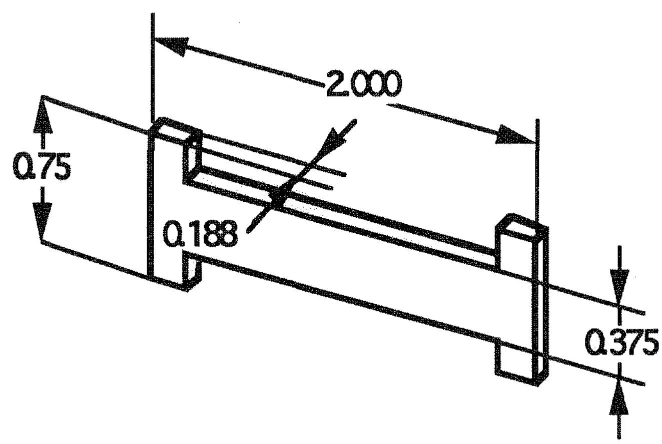

Figure 4: Test Part

The two hatch types chosen were TRIHATCHand STARWEAVE™. The TRIHATCH pattern leaves a large portion of the part in the liquid state. Post curing must be used to solidify the honeycomb trapped volumes and results in internal stresses. The STARWEAVE hatch style was developed to reduce those internal stresses. The pattern is formed by creating orthogonally alternating layers of fingers that are not all attached to their respective ends. Furthermore, the hatch overcure is selected so the layers are not completely attached. Since curl distortion is related to the extent of shrinkage after contact with the previous layer, the delayed shrinkage is expected to reduce curl distortion.

Layer thicknesses of 5 and 10 mils were chosen for this study. These values are commonly used by many users and they are usually selected to meet accuracy and build speed requirements.

Hatch spacing is the distance between parallel vectors used to hatch the interior of the part. If the hatch spacing is very small, the solidifying vectors will overlap causing a completely solid layer. Large hatch spacings allow liquid polymer to be trapped in the part to be solidified in the postcureing operation. Values were selected for each hatch style to avoid complete vector overlap and show the postcure effects.

Hatch overcure is the depth that one cured vector "string" pierces into the lower adjacent layer. This is what keeps the individual layers connected together to form a complete part. Although the major portion of the STARWEAVE vectors are not intended to overlap, multiple exposures at vector intersections are expected to "nail" the layers together at points. The TRIHATCH construction superimposes vector scans creating a line connection between layers. Hatch overcures were selected to try to make sure the parts had sufficient layer overlap to prevent delamination and give good "green" strength. Nominal hatch overcures of 6 mils are usually recommended for TRIHATCH and a -1 mil overcures (1 mil undercure) is a common starting point for STARWEAVE.

Fill cure depth is the depth of the solid layers formed on the upper and lower faces of the solid. This holds the remaining liquid inside the part for subsequent post-curing. Skin fill s are required for the TRIHATCH style , but are sometimes eliminated in STARWEAVE.

Many other parameters need to be defined for a complete build. These remaining variables were all held constant. The Appendix gives the complete setup for the 3D Systems SLA-250 used to create the parts.

RESULTS

The following tables show the chord height for each of the pieces made as measured by a dial depth gage. Positive values indicate an upward curl as shown in Figure 3, while negative values indicate sag. An "X" indicates that the style was not able to produce a viable solid (e.g. insufficient green strength or delamination). All dimensions are in mils (0.001 inches).

Tables III through V show a large number of failures and thus there was not enough data to make a complete statistical evaluation. However, some qualitative observations can be made. For the TRIHATCH with 5 mil layer thickness, one can estimate that the 30 and 50 mil hatch spacings were too far apart, with 30 mils close to the upper limit. Therefore, more experiments need to be

Table II: 10 mil Layer TRIHATCH

Hatch Spacing:	10			30			50		
Hatch Overcure :	-2	2	6	-2	2	6	-2	2	6
Fill Cure Depth:									
5	24	20	17	-6	-13	21	X	-16	-7
15	11	13	16	4	0	0	16	35	0
25	15	18	21	-8	0	10	-12	-6	-7

Table III: 5 mil Layer TRIHATCH

Hatch Spacing:	10			30			50		
Hatch Overcure :	-2	2	6	-2	2	6	-2	2	6
Fill Cure Depth:									
5	13	22	18	X	-17	4	X	X	-10
15	7	14	18	X	-8	-8	X	X	1
25	5	20	15	X	-7	6	X	X	11

Table IV: 10 mil Layer STARWEAVE

Fill Cure Depth:	0			12.5			25		
Hatch Overcure :	-2	-1	0	-2	-1	0	-2	-1	0
Hatch Spacing:									
10	31	37	29	14	21	21	13	16	10
15	X	X	4	11	15	29	3	2	-10
20	X	X	X	15	13	3	10	55	43

Table V: 5 mil Layer STARWEAVE

Fill Cure Depth:	0			12.5			25		
Hatch Overcure :	-2	-1	0	-2	-1	0	-2	-1	0
Hatch Spacing:									
10	X	39	25	22	24	16	X	2	11
15	X	X	X	X	X	4	10	9	X
20	X	X	X	X	X	25	X	X	X

performed with hatch spacings between 10 and 20 mils. For the STARWEAVE style, the curl values are all fairly large. It seems that the range of parameter values chosen were not appropriate for the STARWEAVE pattern. More experiments need to be performed with different parameter values or perhaps different parameters. This indicates more understanding and practical experience with the TRIHATCH pattern.

The only set to give enough data was the TRIHATCH with 10 mil layer thickness. Qualitatively, Table II indicates curl minimization near the 30 mil hatch spacing which matches our experience. To study the data, we first performed a three-way layout with one observation per cell analysis of variance. The three factors were hatch spacing, hatch overcure and fill cure depth:

$$h(i,j,k) = K + A(i) + B(j) + C(k)$$

where K is a translational constant and A, B, C represent the effects of the three parameters: hatch spacing (i=1,2,3 corresponds to 10,30,50 mils), hatch overcure (j=1,2,3 corresponds to -2,2,6 mils) and fill cure depth (k=1,2,3 corresponds to 5,15,25 mils) respectively. Unfortunately, a simple linear model with just those three variables was able to account for less than 40% of the total variance between the model and the data; $R = 0.35$, where R is the typical correlation coefficient used in least-squares analyses. Next, the three-way layout was performed with the model:

$$h(i,j,k) = K + A(i) + B(j) + C(k) + AB(i,j) + AC(i,k) + BC(j,k)$$

where again, K is a constant and A B C represent the effects of the three parameters, but now AB, AC and BC represent the effects of the combined parameters of hatch spacing with hatch overcure, hatch spacing with fill cure depth and hatch overcure with fill cure depth respectively. This model was able to account for over 80% of the variance ($R = 0.90$) and thus gives a reasonable model estimate of the data. However, an estimate of the standard deviation of the experimental curl observations is fairly large at 5.637 mils and indicates the need for more experiments. Nevertheless, we have enough data to determine the relative importance of the various effects (A, B, C, AB, AC and BC) by testing the hypothesis that all values of any specific parameter are 0; that is the parameter has no effect on the curl. Table VI shows the probability that the particular parameter has no effect on the curl.

Table VI: Relative Importance of Parameters

Source	Probability of NO effect
Hatch Spacing	2.15%
Hatch Overcure	89.28%
Fill Cure Depth	39.02%
Hatch Spacing x Hatch Overcure	28.75%
Hatch Spacing x Fill Cure Depth	19.46%
Hatch Overcure x Fill Cure Depth	25.69%

From this, we can conclude that the most statistically significant parameter is the hatch spacing.

Given the results from the analysis of variance, we attempted to fit the experimental data to a quadratic function of the three variables; that is:

$$h = K0 + K1*x + K2*y + K3*z + K4*x*y + K5*x*z + K6*y*z+ K7*x*x + K8*y*y + K9*z*z$$

where the K0, K1, ... K9 constants were determined by a least-squares minimization of error and the variables x,y,z represent hatch spacing, hatch overcure and fill cure depth respectively. Unfortunately, this model can only account for a little over 40% of the variance (R = .64) and thus indicates the need for more experiments to get better statistical curl information for the parameters and/or the need for a different mathematical model to predict curl.

An additional source of error in these experiments could have been the cleaning of the test pieces. No solvents were used in cleaning the parts because of their known influence on curl and swell. Some parts were very delicate and could have been damaged when their supports were removed.

Recommendations for further experiments are to:

1. Rebuild pieces to obtain statistical measures of curl for a single set of build parameters,

2. Build the TRIHATCH pieces with more hatch spacing values between 10 and 20 mils, and

3. Build more STARWEAVE pieces to determine more appropriate build parameters.

CONCLUSION

In this paper we experimentally studied the effect of various parameters on the curl distortion in parts built using stereolithography. From our experiments, only the TRIHATCH build with 10 mils layer thickness had enough data for statistical evaluation. However from observation, our experiments indicate that it is difficult to produce good parts with no fill cure depth More parts need to be built with the STARWEAVE style to determine how those build parameters affect curl. Our results for the 10 mil TRIHATCH show that there are important cross relationships between the hatch spacing, the hatch overcure and the fill cure depth In addition, the hatch spacing is the single most important parameter affecting the curl. We were not able to generate an acceptable quadratic model for our experimental data and suggest further experiments.

REFERENCES

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2. Richter, J. and P.F. Jacobs, "The Present State of Accuracy in Stereolithography," Proceedings of the Second International Conference on Rapid Prototyping, Dayton, Ohio, 1991.

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5. Weissman, P.T, Bolan, B.A., and Chartoff, R.P., "Measurements of Linear Shrinkage and the Residual Stresses Developed During Laser Polymerization," Proceedings of the Third International Conference on Rapid Prototyping, Dayton, Ohio, 1992.

APPENDIX

Model:

Create Solid Model (Using Aries Software, Version 4)
Create Support Structure
Create Array of Test Parts
Orient and Position Parts
Convert to SLA Interface File
Transfer File to SLICE Computer

Slice: (SLA-250 3D Stereolithography System Version 1.8 Release 3.82.1, copyright 1990, 3D Systems, Inc.)
Select SLICE Parameters

Parameter	TRIHATCH	STARWEAVE	
Scale Factor	1	1	
Slice Resolution	5000	5000	
Layer thickness	fixed	fixed	(0.01 or 0.005)
X hatch space	variable	variable	
Y hatch space	0	0	
X skin fill	0.004	0.004	
Y skin fill	0	0	
Min. Surf. Angle	0	50	
Beam Comp.	0	0	
Slice Axis	Z	Z	
Staggered hatch	OFF	ON	
Alt. Sequence	OFF	ON	
Retracted hatch	OFF	ON	

Execute slice

Process:

Import Slice file to SLA-250 machine
Select files to be merged and offset
MERGE: Create vector layer parameter range files
Select range parameters
Add ranges: define 3100 for 10 mil and 3075 for 5 mil
Recoater
    Range 1: NS 0; ZA .5; ZV .5; ZW 5; PD 1
    Range 2: NS 1; ZA .5; ZV .5; ZW 10; PD 1; P1 17
Vector Cure Depths
    Border overcures: 0.008 supports, 0.006 parts
    Hatch overcures: 0.008 supports, (Table I) parts
    Fill cure depths: (Table I) parts
Update range file
Set-up machine:
    Verify laser beam power (18mW)
    Verify material (DuPont SOMOS™ 3110)
    Verify vat conditions (fill level and 30C temperature)
Build parts

Finish:

Drain parts over vat
Remove parts from SLA
Remove excess resin from parts:
    absorbant swab, NO solvent used
Remove parts from platform
Remove supports
Continue excess resin removal
Post-cure: UV oven for ten minutes per side