REDUCING WARPAGE IN STEREOLITHOGRAPHY THROUGH NOVEL DRAW STYLES

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ABSTRACT

A consistent problem with stereolithography has been part distortion and dimensional inaccuracies caused by resin shrinkage. Resin shrinkage and, thus, warpage occurs during the build process and during the postcure. Build parameters such as draw pattern (the order in which strands are drawn by the laser) and overcure (cure depth minus slice thickness) can affect overall part warpage by minimizing the warpage of individual strands and layers. A software package, PATTERNDRAW, developed at the University of Dayton allows an SLA operator to manipulate vector files and change the pattern by which layers, slices, are filled in. This software was used to study the effects of draw pattern, vector segmentation, and cure depth on warpage of parts of different sizes. All parts were made using Ciba-Geigy 5081-1 resin. Moire analysis was used to measure out-of-plane deflections of part surfaces. Results indicate that significant reductions in warpage can be achieved by the use of novel draw styles.

INTRODUCTION

A consistent problem with stereolithography is part distortion and dimensional inaccuracy. Shrinkage caused by resin-curing unsymmetrically relative to the mid-plane of the strands, layers, and part is the principal cause of warpage. As the resin cures, material properties and shrinkage change with time. Consequently, the order in which the vectors or strands are drawn relative to one another, which is a time-dependent process, affects warpage. Others [1,2] have shown that particular draw styles (such as STARWEAVE™) can reduce warpage and dimensional inaccuracy. This paper shows how further reductions in warpage are possible by considering vector randomization and segmentation.

EXPERIMENTAL

An SLA-250 stereolithography machine was used to make test parts with Ciba-Geigy XB 5081-1 resin. Specific test part geometries are discussed below. Layer thickness was held constant at 0.010" (0.025 cm). Center-to-center vector spacing was also held constant at 11 mils (0.028 cm). This vector spacing was determined to be optimal for the STARWEAVE™ draw style on our SLA-250 machine. Warpage was measured using a moire analysis apparatus. Parts were coated with a thin layer of titanium dioxide powder (nominal diameter 0.2mm) to enhance reflectance for the moire analysis. A description of the particular moire apparatus used is given in [3]. Parts measured in the "green" state were first removed from the platform and supports. Parts to be postcured were also removed from the platform and supports before postcure. Postcure was conducted in three stages: bottom side up for two hours using four lamps (40 watts each) then top side up for two hours using four lamps, and finally, top side up for two hours using eight lamps.

Part Geometries

The following part geometries were tested: 2" x 2" x 0.08" (5.08 x 5.08 x 0.2 cm) plates, 2" x 2" x 0.08" plates with stress concentrators, 6" x 6" x 0.25" (15.24 x 15.24 x 0.64 cm) slabs, and twin cantilevers. Both the 6" x 6" slab and the twin cantilevers are standard 3D Systems test parts and are described in [4]. The dimensions of the twin cantilever specimens are cited below.

The 2" x 2" plate with stress concentrators includes a hole 0.60" in diameter which provides stress concentration, and legs 0.25" x 0.25" x 0.375" in length which pin down the corners and thus promote curl at the edges. Supports for this part did not extend to the outside edge, but to the inside edge of the legs only.

Briefly, the twin cantilever curl test involves building 8 identical parts at one time and measuring the curl deflection in each arm of each part in the "green" state. The cantilever arms are 6 mm thick and 3 mm wide. The unsupported length of each arm is 14 mm. The curl factor C_{f6} is defined as [4]:

$$C_{f6} = (M_6 - M_0)/6 \text{ mm} \bullet 100 \qquad \text{Eq. 1}$$

where M_6 = the thickness of the cantilever arm measured 7 mm away from the base (nearest edge)
M_0 = the thickness of the cantilever arm measured 1 mm away from the base (nearest edge).

The required measurements were made using electronic calipers accurate to 0.001 mm. All measurements were made within 24 hours after building the parts.

Moire Analysis

Moire analysis generates fringe patterns in which the fringes represent out-of-plane deflections similar to the lines on a contour map. The technique is accomplished by projecting a fringe pattern onto the object of interest, then viewing the object from a different direction [5]. Another fringe pattern is placed in the viewing path where it acts as an analyzer, reducing the data interpretation to fringe topography.

The out-of-plane displacement associated with each fringe or contour can be calculated from the expression

$$w = p/(\tan\alpha + \tan\beta) \qquad \text{Eq. 2}$$

where: w is out-of-plane displacement,
p is the grating pitch (1/lines per inch),
α is the angle between the analysis axis and the normal to the reference plane, and
β is the angle between the reference axis and the normal to the reference plane.

For all experiments, p was 0.004, α was 45 degrees and β was 0.0 degrees. Therefore, the fringe-to-fringe (e.g., black-to-black or white-to-white) spacing represented 4 mils (0.10 mm) of deflection. Thus, using interpolation, about 0.5 to 1.0 mil of deflection was measurable. The image is enhanced through the use of a video signal processor. The reconstructed image is displayed on a video monitor and photographed for final analysis. A perfectly flat surface would appear all black. A bowl shaped object would appear as a series of concentric rings with the spacing of the rings proportional to the curvature of the object. Out-of-plane deflection (w) is manually recorded as a function of the x and y (in-plane) dimensions.

Draw Styles

A software package developed by Li [6], called "PATTERNDRAW", allows the operator to manipulate the SLA-250 vector files when building parts. The software both restructures the sequence in which the vectors are to be drawn and permits segmentation of the vectors. Vectors can be drawn in patterns called: Alternating, Centered, or Random. The Alternating pattern draws every other vector from left to right in a first pass and the remaining vectors are drawn in a second pass. With the Centered pattern, vectors are drawn from the center of the part outwards alternating between vectors left of center and vectors right of center. Finally, with the Random pattern vectors are assigned numbers and then a random number generator is used to select the draw order.

In most cases, all vectors in one direction (e.g., x) are drawn before the orthogonal vectors and this order is referred to as X/Y. The specification "Total" groups all vectors (x and y) together. Since strands or vectors are not drawn in a sequential manner, individual strands can shrink independently. Strands can be drawn retracted from the border as is done in STARWEAVE™. The PATTERNDRAW software also allows the border to be drawn last instead of first. This option can minimize the border displacement caused by shrinking fill vectors.

The vector segmentation feature is based on the idea that the maximum deflection of each strand is a function of the curvature (which is material-property-dependent) and the length of the strand. For example, a beam that is fixed at one end and has bending moments applied at both ends has a maximum deflection proportional to the square of the beam length [7]. By reducing strand length, we can reduce net warpage. Vectors can be segmented with or without spaces between. The segments making up a layer can be drawn randomly or sequentially. As a result, pattern style, segment length, and segment spacing all needed to be studied.

Cure depth or overcure is another important parameter to be studied. Overcure affects the overall degree of cure of strands and the cure profile in the depth or z direction. Strands are cured from the top down by the passing laser. Warpage of individual strands occurs because a greater volume of resin above the mid-plane of the strand is cured above the gel point than the corresponding volume of resin below the mid-plane of the strand. The higher the degree of cure the higher the amount of shrinkage. Hence, greater overcure, which causes a greater degree of cure in a strand, should result in more warpage. However, if the cure profile in the z direction can be made more symmetric by curing deeper into the layer below, less warpage should occur. These last two statements are contradictory and, indeed, contradictory results were obtained using overcure depending on the in-plane dimensions of the parts built.

RESULTS AND DISCUSSION

For all part geometries tested, reductions in warpage compared with the standard STARWEAVE™ draw style were achieved. The effects of draw pattern, vector segmentation, and cure depth were evaluated using one or more of the various test geometries, and are summarized below.

Draw Pattern

In addition to STARWEAVE™, three draw patterns were evaluated: Alternating, Centered, and Random. In general, it has been observed that the Alternating pattern is preferable to the others for reducing warpage and improving dimensional accuracy. The Random draw styles can be effective in reducing warpage, however, dimensional inaccuracies may occur with some geometries. When the laser draws vectors in a random order it crisscrosses the vat many times. As a result, holes or open areas in the part may be filled in by the laser movements.

Two geometries were used to compare draw patterns alone. Experiments in which draw pattern was tested in combination with other parameters (e.g., overcure) are discused in subsequent sections.

Slab 6*6. All 6*6 slabs were measured twice, once in the green state after removal from the platform, and once after postcure. The deflection or warpage of the bottom surface was measured. This is an important point. The curvature or deflection of the top surface of a thick part will not reflect the amount of warpage occurring in the vat during part building particularly for high-shrinkage resins like XB5081-1. In fact, from past measurements of 2" x 2" x 0.25" slabs we observed that the greater the warpage in the bottom surface, the less the warpage in the top surface. High warpage in the first few layers creates a "bowl" which is filled in by subsequent layers.

The Alternating X/Y pattern produced a postcured part with 7% less maximum corner deflection than STARWEAVE™ (199 mil versus 215 mil). When Alternating X/Y was used with the Border Last option, the reduction in maximum corner deflection was 16% compared with STARWEAVE™ (180 mil versus 215 mil).

3D Systems Twin Cantilever. Two draw styles were tested, STARWEAVE™ and Alternating X/Y. The average curl factor for the Alternating pattern was measured to be 34% lower than that for STARWEAVE™. The STARWEAVE™ part had a curl factor of

26.4% with a standard deviation of 3.4. The Alternating X/Y part had a curl factor of 17.5 with a standard deviation of 3.4.

Vector Segmentation

In studies of 2" x 2" x 0.08" plates it was found that the optimal segment spacing was zero. That is, leaving no space between the segments minimizes the amount of resin to be cured in the postcure oven and, as a result, minimizes warpage. To use zero spacing and still reap the benefits of segmentation, the vectors cannot be drawn sequentially. Any of the patterns used for whole vectors, such as Alternating, can also be used for segments.

Vector segmentation was used with Alternating X/Y, Random X/Y, and Random Total draw patterns. In most studies, overcure was used in combination with vector segmentation. Only one geometry, Slab 6*6, tested vector segmentation without overcure.

Slab 6*6. Vector segmentation was used in combination with the Alternating X/Y draw style. The segment size used was 0.5". The average corner deflection for the postcure segmented-vector part was 22% less than that for the STARWEAVE™ part; and the maximum corner deflection was 33% less (144 mil versus 215 mil). These improvements are much better than those for the part made using the Alternating X/Y pattern without vector segmentation. It is suggested that the larger the part, the more vector segmentation becomes important.

Overcure

Varying amounts of overcure were tested to evaluate its effects on warpage. For a 2" x 2" part it was found with a 10 mil slice thickness that warpage reduction was maximized with 6 mil of overcure. This was true with and without vector segmentation. For a 2" x 2" part with a 5 mil slice thickness, an overcure of 3 mils also produced flat parts. The difference in out-of-plane deflections between parts made with and without significant overcure was dramatic. As is discussed below, for the 2" x 2" plates maximum corner deflection was reduced by 79% by using 6 mil of overcure for a 10 mil slice thickness. There was some variation in effectiveness of overcure depending on draw pattern, but overcure was overwhelmingly more important in reducing warpage in small (2" x 2") parts than was draw pattern. The exact opposite was observed in large parts made with 6 mils of overcure. For the Slab 6*6 parts, overcure produced very warped parts.

Slab 6*6. The STARWEAVE™ pattern with 6 mils of overcure was compared with the STARWEAVE™ pattern using 0 mil of overcure. The part with overcure had 43% more maximum corner deflection than the standard STARWEAVE™ part. This result is in direct contrast to the results for 2" x 2" plates, suggesting that vector segmentation combined with overcure is necessary for building flat 6" x 6" or larger parts.

2" x 2" x 0.08" plates. A large number of 2" x 2" x 0.08" plates were made using both WEAVE™ and STARWEAVE™ (with and without overcure), Alternating/segmented-vector (with overcure), and the Random/segmented-vector (with overcure) draw patterns. Also, the Border Last option was tried with the above draw patterns. The best results were achieved using 6 mil of overcure. With a 6 mil overcure, the warpage reduction was great regardless of a particular draw pattern. The standard STARWEAVE™ part with no overcure had a maximum edge deflection of 26 mil and a maximum corner deflection of 38 mil. When the STARWEAVE™ pattern was used with 6 mil overcure the maximum edge and corner deflections were reduced to 10 mil and 14 mil respectively. (When the Border Last option was used along with overcure the deflections were 10 mil and 10 mil respectively.) The best overall results were achieved with the

Random/segmented vector draw style (6 mil overcure) which had maximum edge and corner deflections of 7 mil and 8 mil respectively. That is, a 79% reduction in maximum corner deflection was achieved. The best results obtained with the Alternating/ segmented vector draw style (6 mil overcure) were 10 mil of maximum edge deflection and 16 mil of maximum corner deflection using a segment size of 200 mil. Detailed results for these parts are listed in Table 1.

Designations used in the Table are as follows.

R indicates Random X/Y draw pattern
A indicates Alternating X/Y draw pattern
SV-a/b/c indicates segmented vectors having a segment size = a, segment spacing = b, and overcure = c.

Unless otherwise indicated, the parts were made with the border drawn first.

2" x 2" x 0.08" plates with stress concentrators. This part which has been referred to as the "potty seat", has a centered hole and is supported by a short leg at each corner. The standard STARWEAVE™ pattern was used twice, once with the border drawn first, and once with the border drawn last. Two Alternating/ segmented vector parts with overcure (6 mil) were made. The parts with overcure had significantly reduced warpage compared with the STARWEAVE™ parts. Specifically, the overcure part having a segment size of 50 mils had 43% less maximum edge deflection (12 mil versus 28 mil) and 54% less maximum corner deflection (10 mil versus 26 mil) than the STARWEAVE™ (border first) part. The decreased warpage resulted in increased dimensional accuracies for the Alternating/ segmented vector parts. The exception was the hole diameter dimension which was poor in all cases due to faceting errors rather than warpage.The average error measured for the sides designed to be 2.0" in length was 1.5 mil for the segmented vector part with 50 mil segments and 4.2 mil for the STARWEAVE™ border first part. Both STARWEAVE™ parts had delamination at the edges; neither overcure part did. The STARWEAVE™ border last part was not flatter than the border first part.

SUMMARY

Three stereolithography build parameters: draw pattern, vector segmentation, and overcure were studied to find ways to decrease or eliminate warpage. These parameters were tested alone and in combination and compared with the 3D Systems draw style STARWEAVE™. Surface deflections were measured using a projection moire apparatus having a precision on the order of 1 mil. Warpage of parts was typically compared by comparing points of maximum deflection such as at part edges and corners. A variety of test geometries was used. Based on the results discussed in the previous sections the following conclusions are made.

1. Small (< 10%) to moderate reductions in warpage (compared with STARWEAVE™) can be gained by using a novel draw pattern such as Alternating X/Y alone (i.e., without vector segmentation or overcure).
2. Greater reductions (> 30%) in warpage can be realized if vector segmentation is employed. The larger the dimensions of the part in the draw plane the more important vector segmentation becomes.

3. For small parts (e.g., 2" x 2" plates) the use of overcure can produce near flat parts with novel draw patterns as well as STARWEAVE™.

4. Overcure used alone, i.e., without vector segmentation, to build large parts (e.g., 6" x 6" plates) can result in increased warpage compared with no overcure.

5. Drawing the border last may result in significant warpage reduction for thick (e.g., 0.25") parts. Drawing the border last is less effective for reducing warpage in thin parts.

More work needs to be done to determine the relative importance of the build parameters: draw pattern, vector segmentation, and overcure as a function of part size and geometry. In particular, we need to assess whether there is a critical vector length at which vector segmentation becomes necessary to significantly reduce warpage.

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Note: STARWEAVE and WEAVE are registered trademarks of 3D Systems, Inc.

Table 1. Edge and Corner Deflections for 2" x 2" x 0.08" Plate Specimens

Draw Style	Overcure (mils)	Max. Edge Deflection (mils)	Max. Corner Deflection (mils)
WEAVE™	-1	30	44
STARWEAVE™	-1	26	38
STARWEAVE™ (+6)	6	10	14
STARWEAVE™ (+6) (Border Last)	6	10	10
Random X/Y	0	30	44
Centered X/Y	0	26	38
Centered Total	0	32	50
A-SV-50/0/6	6	10	20
A-SV-50/0/6 (Border Last)	6	14	20
SV-A-100/0/6	6	10	22
SV-A-100/0/6 (Border Last)	6	14	24
SV-A-200/0/6	6	10	16
SV-A-200/0/6 (Border Last)	6	14	30
R-SV-100/10/6	6	20	30
R-SV-200/10/4	4	20	28
R-SV-50/0/5	4	17	22
R-SV-50/0/8	8	8	12
R-SV-100/0/6	6	7	8
R-SV-50/0/6	6	8	10