

Studies in Stereolithography : Influence of Process Parameters on Curl Distortion in Photopolymer Models

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Abstract

To make the stereolithography process more useful in the manufacturing industry, the dimensional accuracy of the parts it creates should be very high. But due to the nature of the polymerization process and the mechanism of laser scanning, distortions are induced in the parts. Curl distortion is a major source of inaccuracy in this photopolymer based technology. This paper approaches the problem from a process related point of view by addressing the major parameters responsible for curl. The work presented here is a continuation of a similar work presented at the SFF symposium in 1993 [1].

Introduction

The need for stereolithography fabricated parts in areas like form and functional inspection, tooling etc., has made it imperative that the parts

made using this process be of a high degree of dimensional accuracy. To build parts with high levels of accuracy a number of factors need to be closely monitored and controlled. However, models built using stereolithography suffer from curl and other distortions which occur during photopolymerization.

Discussion

Curl distortion in stereolithography parts is a consequence of the stresses induced in the cured material during acrylate polymerization [2]. Curl may be defined as any out-of-plane deflection of a flat layer and is the result of inter layer shear stresses generated during the solidification process . It occurs in a wide range of situations and is dependent mainly on the properties of the photopolymer, the part design, the part building procedures and the post processing methods used. A few empirical criteria have been proposed to minimize curl. They essentially address the inherent material characteristics like the rate of polymerization and the shrinkage behaviour of the polymer.

This study focuses on the problem of curl from a build process point of view. Hence those parameters which determine the build cycle have been identified for experimental investigation. Five essential parameters have been selected based on a similar study done earlier [1]. they include layer thickness, writing style, hatch spacing, hatch over cure and fill cure depth. Layer thickness is controlled by the laser beam intensity and is the thickness of each layer drawn on the liquid surface. It is the thickness used by the slice software to partition the CAD model into layers. Writing styles are primarily distinguished by the methods of printing hatch vectors. They are essentially a combination of border, hatch, fill vectors and overcures used to create a solid imaged part by stereolithography. Hatch spacing is the distance between the centerlines of adjacent parallel hatch vectors used to hatch the interior of the part. Fill cure depth is the depth of the solid layers formed on the upper and lower faces of the solid part. A more detailed discussion on these terms can be found in reference [3]. The rationale behind the parameter selection is better understood by taking a closer look at the way stereolithography process generates three-dimensional parts. There are a few essential building blocks that make part generation possible.

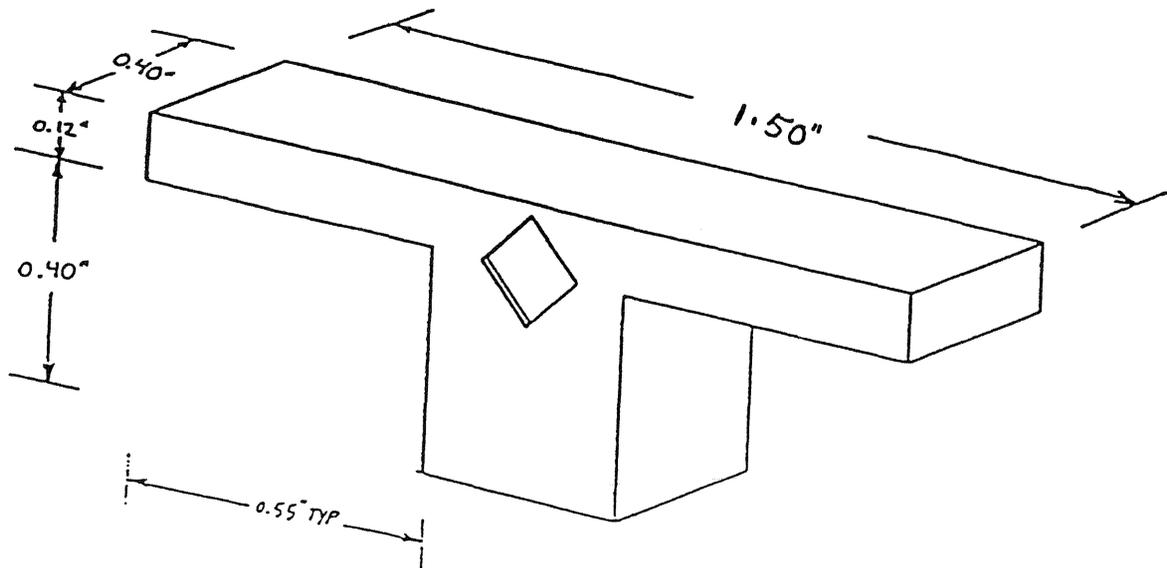


Figure 1: Twin-Cantilever Test-Piece

- a finite set of layers of uniform thickness which make up the three-dimensional object.
- a series of uniformly spaced laser scanned photopolymer strings which constitute the individual layers.
- sufficiently thick photopolymer strings which tack successive layers of material to form a laminated object.
- closely drawn top and bottom boundary layers which hold the newly formed part together.

In order to study the influence of variations in the parameters described above on the magnitude of curl, a twin cantilever test-piece has been chosen [4]. The test-piece is illustrated in Fig 1.

The chord height of the distorted twin cantilever surface has been used as a measure of the curl induced. A number of test-pieces were built using different ranges of these parameters. Two different writing styles- Hatch and Weave have been investigated. Table 1 and Table 2 show the ranges of the

Table 1: Ranges of the Process Parameters for Hatch Writing Style

| parameter | value |
|------------------|--------------|
| Layer Thickness | 10 5 7.4 |
| Hatch Spacing | 20 30 |
| Hatch Overcure | -2 2 5 6 |
| Fill Cure Depth | 5 15 25 |

four parameters- layer thickness, hatch spacing, hatch overcure and fill cure depth, used to build parts with hatch and weave styles respectively. In the study the weave writing patterns two more parameters have been included ; namely, retraction (RET) and alternate-staggering (ALTS). All values are in mils (.001 inch).

The choice of these range values was based on the ease of processing the parts and the build time efficiency. It has been found that layer thickness directly controls build cycle times [3]. If thickness of the layers is held below 5 mils, then the recoating process consumes a great majority of the time. If layer thicknesses above 10 mils are chosen, the build cycle efficiency drops because the laser scan velocity needs to be kept low in order to draw thicker layers. Hatch spacing values between 10 mils and 35 mils were chosen because levels lower than 10 mils increase build times while levels above 35 mils leave a considerable fraction of the liquid in the uncured state.

Owing to the nature of the weave patterns, the hatch spacing values have been held low in the weave writing style in order to generate parts with sufficient green strength. The choice of values for hatch overcure was based on the principle of balancing the opposing effects of layer delamination and curl distortion. Earlier studies indicate that the values of fill cure depth between 0 mils and 25 mils produce good results [1].

With these range values a number of test-pieces were built. However, it has been observed that with particular combinations of these various parameters the part building was unsuccessful. For the purpose of analysis a part is considered to have failed if it does not meet the following two conditions:

Table 2: Ranges of the Process Parameters for Weave Writing Style

| parameter | value |
|------------------------|--------------|
| Layer Thickness | 5 10 |
| Hatch Spacing | 9 12 |
| Hatch Overcure | 0 2 |
| Fill Cure Depth | 0 25 |
| Retraction | Off On |
| Alternating-staggering | Off On |

- if it does not have enough green strength to hold together while being removed from the build platform, or
- if after the postcuring operation, layer delamination occurs and the dimensional integrity of the part is lost.

The material used for the experimental study is the Du Pont SOMOS 3100 solid imaging photopolymer [5]. The test-pieces which have been successfully built were removed from the platform, cleaned in a blast of dry air and postcured in a UV oven for 10 minutes. The postcured parts were then measured for curl by estimating the chord height of the cantilevers using a dial gauge. Next, the resulting data has been statistically analysed. First, an analysis of variance (ANOVA) was performed on the data to test for the relative importance of the parameters. In performing the analysis of variance, a full factorial model was considered and the influence of all the main and interaction effects computed. A factorial experiment is an experiment which extracts information on several design factors more efficiently than can be done by the traditional tests involving the study of the effect of a single factor on some characteristic. The main objective in a factorial experiment is to determine the effect of various factors (independent variables) on some characteristic of a product (dependent variable) of interest. Linear analysis of models can be applied to study these kinds of situations. The principle on which the analysis of variance (ANOVA) works is that, when several sources of variations are acting simultaneously on a set of observations, the variance

in these observations is the sum of the variances of the independent sources. This property makes the application of ANOVA particularly useful in factorial experiments. By this method, the total variation within an experiment can be broken down into variations due to each main factor, interacting factors, and residual (experimental) error. The significance of each variation is then tested.

From this analysis a selection of variables was made depending on contribution of each of these terms to the model sum of squares and their significance, as determined by a F-test. The term **Pr** indicates whether a particular parameter is significant in explaining the variation in the model. A Pr value less than .05 denotes that the parameter is important [6]. Based on the results of this analysis, statistically significant terms have been chosen to describe the model. For the purpose of analysis the hatch and weave styles have been treated separately.

With the hatch writing style a total of 160 different specimens were successfully built using various combinations of layer thickness, hatch spacing, fill cure depth and hatch overcure. In order to minimize discrepancies during part building and measurement errors, four identical sets of these 160 specimens were built and the mean value of the curl at each combination of these four parameters was used for the analysis. Particular combinations of these four parameters resulted in failed parts. They have not been considered in the data analysis. The results of the data analysis are presented in Table 3.

Table 3 shows the statistically significant terms. DF represents the number of degrees of freedom. SS is the sum of squares of the terms while MS represents the mean sum of squares of the terms. F value is the ratio of the mean sum of squares of the model and the mean sum of squares of the error. F ratio judges the significance of the model as a whole after fitting the intercept. Pr, which is the significance probability for a particular value of F is a test of the hypothesis that all parameters except the intercept are zero. The significance probability measures the probability that you would get an even larger F value given the hypotheses to be true. This test is usually very significant since most regression models fit better than the simple intercept model.

A more detailed description of these terms can be found elsewhere [6]. The

Table 3: Results of the ANOVA Procedure- Hatch Writing Style

| Source | DF | SS | MS | F value | Pr |
|-----------------|-----|----------|---------|---------|--------|
| Model | 24 | 18933.96 | 788.91 | 136.26 | 0.0001 |
| Error | 135 | 781.60 | 5.79 | - | - |
| Corrected Total | 159 | 19715.56 | - | - | - |
| LT | 2 | 40.63 | 20.32 | 3.51 | .0327 |
| HS | 1 | 4010.70 | 4010.70 | 692.74 | .0001 |
| FCD | 2 | 3210.53 | 1605.27 | 277.27 | .0001 |
| HOC | 2 | 2067.56 | 1033.78 | 178.56 | .0001 |
| LT*HS | 2 | 59.02 | 29.51 | 5.10 | .0073 |
| LT*FCD | 4 | 161.05 | 40.26 | 6.95 | .0001 |
| HS*FCD | 2 | 3844.02 | 1922.01 | 331.97 | .0001 |
| LT*HOC | 4 | 141.55 | 35.39 | 6.11 | .0001 |

Table 4: Results of the ANOVA Procedure- Weave Writing Style

| Source | DF | SS | MS | F value | Pr |
|-----------------|-----|----------|---------|---------|--------|
| Model | 10 | 5628.101 | 562.81 | 14.85 | 0.0001 |
| Error | 109 | 4132.38 | 37.91 | - | - |
| Corrected Total | 119 | 9760.48 | - | - | - |
| LT | 1 | 570.05 | 570.05 | 15.04 | .0002 |
| HS | 1 | 953.07 | 953.07 | 25.14 | .0001 |
| FCD | 1 | 710.61 | 710.61 | 18.74 | .0001 |
| HOC | 1 | 2375.74 | 2375.74 | 62.67 | .0001 |
| RET | 1 | 520.29 | 520.29 | 13.72 | .0003 |
| ALTS | 1 | 8.81 | 8.81 | .23 | .6308 |
| HS*RET | 1 | 340.62 | 340.62 | 8.98 | .0034 |
| HS*HOC | 1 | 254.86 | 254.86 | 6.72 | .0108 |
| LT*RET | 1 | 272.24 | 272.24 | 7.18 | .0085 |
| LT*HOC | 1 | 986.65 | 986.65 | 26.02 | .0001 |

results of the analysis show that the four main parameters: layer thickness (LT), hatch spacing (HS), fill cure depth (FCD) and hatch over cure (HOC) and the interactions between LT & HS, LT & FCD, HS & FCD and LT & HOC explain around 95 % of the variation in curl. The mean value of curl for the entire set of observations has been found to be around 3.3 mils. A more detailed presentation of the results can be found in reference [7].

With the weave writing style a total of 120 different specimens were successfully built. Part failures in this style were significantly higher than in the hatch style. The results of the data analysis are presented in Table 4. Analysis of the results obtained for specimens built using weave styles shows that the main parameters: LT, HS, FCD, HOC and RET and the interactions between HS & RET, HS & HOC, LT & RET and LT & HOC are significant. However, The results indicate that these parameters account for only around 57 % of the variation in the distortion [7]. Interestingly, the influence of alternate staggering on the curl is not significant. The average value of curl distortion obtained for the entire set of data presented in Table 4 is around 25.3 mils.

From the results obtained so far it is observed that the hatch writing style yields better results than the weave style. It was possible to generate dimensionally more accurate specimens using the hatch style. With regard to the hatch writing style it is possible to define a working domain, wherein consistently good and accurate parts can be built [7]. More experiments need to be conducted to study the high failure rate of the weave specimens and the high magnitude of curl distortion observed in those parts which were successful.

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