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Effect of Hatching Strategy on the Dimensional Accuracy of Components Manufactured Using the Stereolithography (SLA) Process

Farid Ghadami*

Department of Mechanical Engineering, Islamic Azad University Science and Research Branch, Tehran, Iran; mania.farid@gmail.com.

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Abstract

Stereolithography (SLA), the first Rapid Prototyping (RP) technology developed, is an additive manufacturing process that enables the direct fabrication of a resin model from a three-dimensional Computer-Aided Design (CAD) model. In this process, each cross-sectional layer of the model is traced by a Ultraviolet (UV) laser beam on the surface of a photosensitive liquid polymer. During the fabrication of each layer, the contour is scanned first, followed by hatching of the enclosed area. The laser exposure cures the hatched region, thereby solidifying the material and forming the desired layer. The dimensional accuracy of parts manufactured by Stereolithography is influenced by several process parameters, among which the hatching strategy adopted for laser scanning of the resin cross-section is one of the most significant. Various hatching strategies have been proposed to optimize this process. In this paper, different hatching methods are introduced and discussed. Furthermore, based on the results of a previous study, the Stereolithography process is modeled using a Multilayer Perceptron (MLP) Artificial Neural Network (ANN). The modeling results indicate that, after layer thickness, the hatching strategy is the second most influential parameter affecting the dimensional accuracy of fabricated parts.

Keywords: Stereolithography, Dimensional accuracy, Artificial neural networks, Multilayer Perceptron, Hatching strategy.

1 | Introduction

Competing in today's global industrial market requires not only high product quality but also significantly increased manufacturing speed to meet rapidly changing market demands. Rapid Prototyping (RP) and Rapid Manufacturing (RM) technologies were developed in response to these industrial requirements. The first

Corresponding Author: mania.farid@gmail.com
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research findings on these technologies were published in 1982, while their first industrial application was introduced through the Stereolithography (SLA) system in California, USA, in 1989 [1], [2].

Unlike conventional subtractive manufacturing processes, RP is an additive manufacturing technology in which components are fabricated through the successive deposition of material in a layer-by-layer manner. Each newly formed layer is automatically bonded to the previous one, and the process continues until the entire part is completed.

Stereolithography (SLA) is an additive manufacturing process that enables the direct fabrication of resin parts from three-dimensional Computer-Aided Design (CAD) models. In this process, a computer-controlled Ultraviolet (UV) laser scans the cross-sections of the CAD model onto the surface of a liquid photopolymer resin. The exposed regions undergo photopolymerization and solidify, while the remaining resin stays in its liquid state [3], [4].

Stereolithography has become one of the most important additive manufacturing technologies due to its ability to produce components with high geometric complexity and excellent surface quality. Improving the dimensional accuracy of SLA-manufactured parts plays a crucial role in expanding its industrial applications and enhancing the overall efficiency of product development and manufacturing.

In general, dimensional errors in RP processes can be attributed to five primary sources [5]:

I. Errors associated with the conversion of CAD models into STL files

II. Errors caused by the finite width of the laser beam

III. Resin shrinkage during polymerization

IV. RP machine setup (process) parameters

V. Post-processing errors.

Among these sources, the approximation errors introduced by STL files have been substantially reduced through the development of newer file formats such as SLC, introduced by 3D Systems in 1992. Likewise, errors associated with the finite laser beam diameter are now largely compensated through software-based beam offset correction algorithms. Resin shrinkage has also been considerably reduced by the introduction of epoxy-based photopolymers, jointly developed by 3D Systems and Ciba-Geigy in 1994. These resins, commercially known as XB5170, exhibit volumetric shrinkage of only 2–3%. Furthermore, the Advanced Curved Edge Scan (ACES) hatching strategy, introduced together with these epoxy resins, significantly reduced dimensional errors associated with post-curing distortion [1], [2].

Consequently, current research efforts are primarily focused on optimizing machine setup and process parameters, which are generally referred to as process parameters.

More than twenty process parameters influence the Stereolithography process, including layer thickness, Z-delay, recoating period, hatch spacing, hatch penetration depth, hatching strategy, part orientation, blade gap, dip speed and acceleration, scanning speed, and several other machine settings. Previous investigations have demonstrated that only a limited number of these parameters exert a dominant influence on dimensional accuracy. Among them, layer thickness, hatching strategy, hatch spacing, hatch penetration, and hatch cure depth have been identified as the most influential factors affecting the dimensional accuracy of SLA-fabricated parts [6].

2 | Hatching Strategies in Stereolithography

Hatching is a commonly employed scanning technique used to solidify the interior region enclosed by the contour boundaries of each layer. Hatch lines correspond to laser scanning vectors and possess a finite width due to the laser beam diameter. Consequently, the enclosed area cannot be completely covered by individual hatch lines alone.

In practice, reducing the spacing between adjacent hatch lines allows the uncured resin trapped between neighboring scan paths to polymerize during the post-curing process, thereby preserving the structural integrity of the fabricated component.

During layer fabrication, the boundary contour of each layer is scanned first, after which the enclosed region is filled using one of several available hatching strategies. The selection of an appropriate hatching pattern significantly influences dimensional accuracy, residual stress, fabrication time, and mechanical properties of the final component.

2.1 | Tri-Hatch Strategy

In the Tri-Hatch strategy, as illustrated in *Fig. 1*, the hatch pattern consists of three sets of parallel scan lines oriented at 0°, 60°, and 120° with respect to the X-axis. The spacing between adjacent hatch lines is typically maintained at approximately 1.27 mm, resulting in a repetitive network of small equilateral triangles throughout the scanned area [7].

This triangular hatching configuration provides a relatively uniform distribution of curing energy and improves structural stability by promoting more homogeneous polymerization across the layer. Consequently, the Tri-Hatch strategy has been widely adopted in Stereolithography systems requiring enhanced dimensional consistency and balanced mechanical performance.

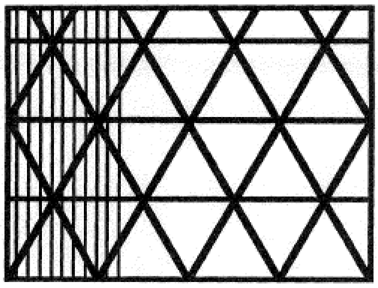

Fig. 1. Tri-Hatch hatching strategy [7].

2.2 | WEAVE Hatching Strategy

In the WEAVE hatching strategy, the laser scan vectors are arranged parallel to the X- and Y-axes. The hatch spacing in both directions is typically maintained at approximately 0.279 mm. For thinner layers, finer hatch spacing is generally required to ensure adequate curing and dimensional consistency. Compared with the Tri-Hatch strategy, the WEAVE pattern provides a considerable improvement in dimensional accuracy owing to its denser and more uniform distribution of scan paths [8].

2.3 | STAR-WEAVE Hatching Strategy

The STAR-WEAVE hatching strategy is an advanced scanning technique derived from the conventional WEAVE pattern. It incorporates three additional concepts: Staggered Hatching (ST), Alternating Sequence (A), and Separated Hatching (R), which are illustrated in *Figs. 2-4*, respectively.

In the STAR-WEAVE strategy, the hatch vectors of the n^{th} layer are generated by offsetting the hatch vectors of the *(n − 1)*th layer by half of the hatch spacing (hs/2) within the same layer. This staggered arrangement effectively eliminates the narrow grooves that typically form between adjacent hatch lines in successive layers.

By reducing the accumulation of uncured regions and improving the overlap between neighboring scan tracks, the STAR-WEAVE strategy enhances dimensional accuracy, promotes more uniform curing, and improves the overall quality of Stereolithography-fabricated components. Consequently, this method has become one of the preferred hatching strategies for applications requiring high geometric precision and superior surface integrity.

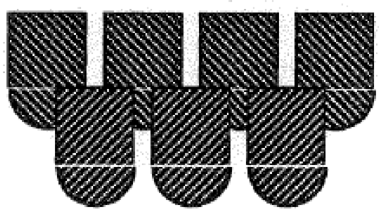

Fig. 2. Staggered Hatch hatching strategy [5].

The alternating sequence concept refers to the repetition of similar layer scanning patterns in an alternating manner. Under this approach, the scanning order of the X and Y hatch vectors alternates between successive layers. Specifically, if the hatch vectors parallel to the X-axis are scanned first in even-numbered layers, then the hatch vectors parallel to the Y-axis are scanned first in odd-numbered layers, and vice versa.

In addition, the direction of hatch vector generation is also alternated between consecutive layers. For example, if in the n^{th} layer the X-direction hatch vectors are generated from the front of the build chamber toward the rear, then in the *(n + 1)*th layer, after the Y-direction hatch vectors have been scanned, the X-direction hatch vectors are generated in the opposite direction, namely from the rear of the build chamber toward the front.

This alternating scanning sequence promotes a more uniform distribution of thermal energy and polymerization shrinkage, thereby reducing directional bias, minimizing residual stresses, and improving the dimensional accuracy and surface quality of Stereolithography-manufactured parts.

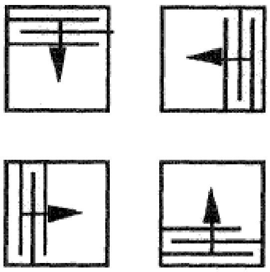

Fig. 3. Alternating sequence in STAR-WEAVE hatching strategy [5].

In the disconnected hatching method, one end of each hatch vector (either in the X or Y direction) is connected to one boundary of the cross-section, while the other end is intentionally terminated approximately 0.2 mm away from the opposite boundary. This small gap helps reduce excessive resin accumulation and residual stresses during curing, thereby improving dimensional accuracy and minimizing distortion of the fabricated part [9], [10].

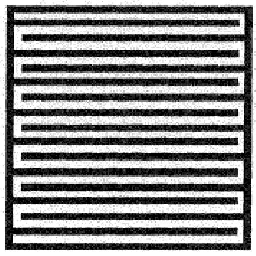

Fig. 4. Separated hatching strategy [5].

2.4 | Divergent STAR-WEAVE Hatching Method

The Divergent STAR-WEAVE (DSW) hatching method, developed by Ono and Hon [5], is based on the findings of Jawahar et al. [11], who demonstrated that shrinkage-induced stresses are generated primarily along the hatching direction. Consequently, alternating the hatching orientation between successive layers produces a more uniform distribution of residual stresses throughout the fabricated part. This more homogeneous stress field significantly improves the dimensional accuracy and overall quality of Stereolithography components.

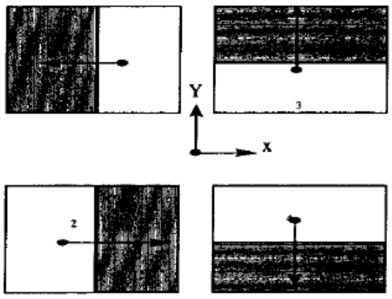

Fig. 5. DSW hatching strategy [5].

Accordingly, in this method, as illustrated in *Fig. 5*, the hatching process begins at the center of the part. The laser first scans from the center toward one edge of the layer and then returns to the center to scan toward the opposite edge. This scanning strategy is applied in both the X and Y directions, following the same alternating sequence used in the STAR-WEAVE method.

2.5 | Diagonal Divergent STAR-WEAVE Hatching Method

The Diagonal Divergent STAR-WEAVE (DDSW) method is a modified version of the DSW strategy, also developed by Revilla [12]. As shown in *Fig. 6*, the scanning vectors are oriented at 45° with respect to the X and Y axes.

According to the experimental results reported by Ono and Hon [5], for a layer thickness of 0.190 mm, this method exhibited the lowest degree of warpage and provided better surface flatness than both the DSW and the conventional STAR-WEAVE methods. However, for layer thicknesses of 0.250 mm and 0.125 mm, they concluded that the STAR-WEAVE strategy remained the most effective hatching method in terms of dimensional accuracy and overall fabrication quality.

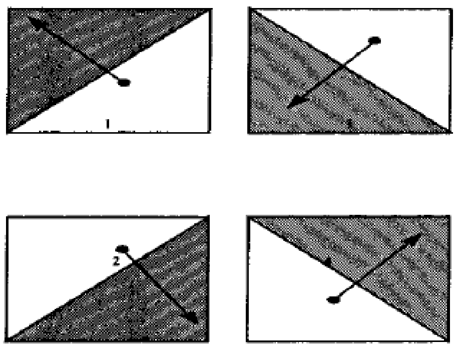

Fig. 6. DDSW hatching strategy [5].

2.6 | Circular STAR-WEAVE Hatching Method

The experimental studies conducted by Ono and Hon [5] also demonstrated that hatching should preferably be performed using shorter scanning paths. This conclusion is consistent with the findings of Ngo et al. [13], who investigated the influence of laser scanning paths on the dimensional accuracy of Stereolithography parts. Their study showed that shorter scan paths lead to higher dimensional accuracy.

The Circular STAR-WEAVE hatching method, developed by Bikas et al. [14], is based on the principle that a more uniform distribution of shrinkage-induced stresses within the fabricated part reduces shrinkage strains and consequently improves dimensional accuracy.

In this approach, the conventional X and Y scanning vectors used in the STAR-WEAVE strategy are replaced by concentric circular and radial scanning paths, respectively. Circular scanning alone does not establish interlayer bonding and therefore generates minimal residual stress. Subsequently, radial scanning is employed to bond the newly fabricated layer to the previous one.

Furthermore, the radial scanning direction alternates between successive layers: in one layer, scanning proceeds from the center outward, while in the following layer it is performed from the outer boundary toward the center. According to the authors, parts fabricated using this method exhibit higher dimensional accuracy than those produced with the conventional STAR-WEAVE hatching strategy under identical processing conditions.

3 | Modeling of the Stereolithography Process Using Artificial Neural Networks

To improve the quality and dimensional accuracy of Stereolithography (SL) components, Ono and Hon [5] conducted an experimental optimization study using the Taguchi statistical design method. Acrylic photopolymer resins were employed, and test specimens were fabricated using an SLA-250 Series 40 Stereolithography machine while systematically varying several process parameters. The resulting specimens were then evaluated to determine the influence of these parameters on dimensional accuracy.

As part of this investigation, the researchers introduced two new hatching strategies, namely DSW and DDSW. These strategies were evaluated together with four additional process parameters, including layer thickness, hatch spacing, hatch cure depth, and solid hatch cure depth, to assess their combined effects on the dimensional accuracy of fabricated parts.

Table 1 summarizes the parameter ranges and the corresponding experimental levels considered in the study.

Table 1. Investigated process parameters and their corresponding levels [5].

Level 3 (mm)	Level 2 (mm)	Level 1 (mm)	Parameter
0.250	0.190	0.125	Layer thickness
—	0.200	0.210	Hatch spacing (A)
—	-0.035	-0.040	Hatch penetration depth (B)
0.200	0.250	—	Solid hatch cure depth (C)

They performed 36 experiments using different combinations of these levels. The desired part was fabricated using three hatching methods, namely Star-Weave, DSW, and DDSW, and its dimensional accuracy was measured. *Fig. 7* shows the experimental sample fabricated in their study (the units are in millimeters). After fabricating each sample with specific parameters, the dimensional accuracy of the fabricated sample was measured along three axes (X1, X2, and Y). The X1 value represents the dimension measured along the upper edge of DC; the X2 value corresponds to the dimension measured along the upper edge of AB; and the Y value represents the dimension measured along the upper edge of BC.

The results obtained from the experimental study of Ono and Hong [5], which had been reported in graphical form, were converted into numerical data in the present study. These data, together with the specified input parameters of the problem, were used for modeling the SL process using a MLP Artificial Neural Network (ANN) implemented in the Easy NN-Plus software.

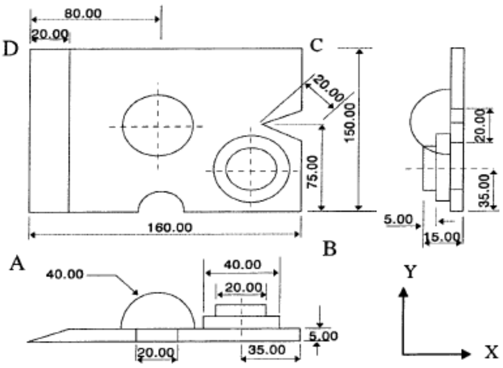

Fig. 7. Part geometry [5].

To model the SL process using a MLP artificial neural network, the layer thickness, hatching method, hatch spacing, hatch penetration, and full cure depth of the hatch were considered as input parameters; while the mean distortion values along the X1, X2, and Y axes were considered as the output parameters of the model.

Furthermore, 33 samples were used for training the software, and three samples were used for its validation.

Fig. 8 illustrates the MLP model developed in this study. As shown in the figure, this model consists of a single intermediate hidden layer with seven nodes. The optimal learning rate and momentum coefficient in this modeling were selected as 0.6 and 0.7, respectively.

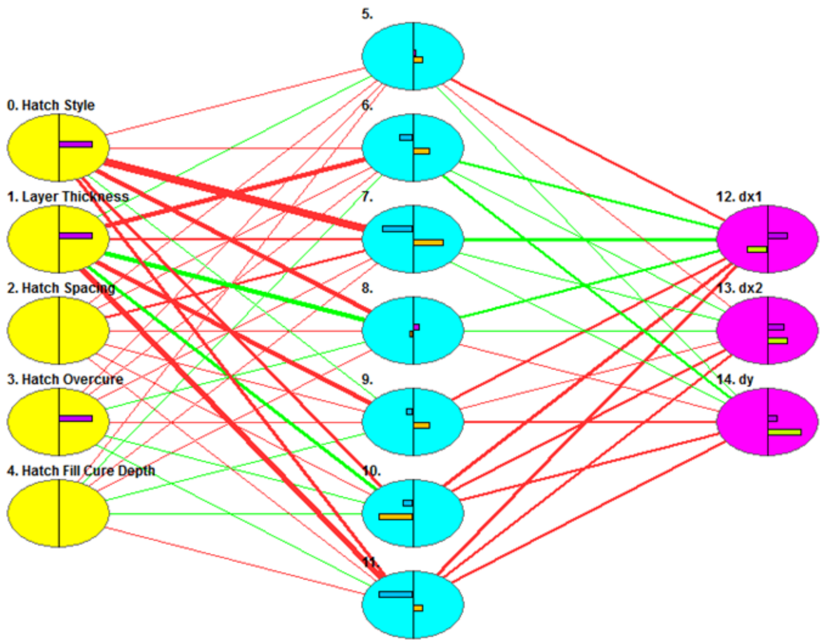

Fig. 8. MLP model used in this study.

To terminate the software training process, a mean training error of less than 0.01 was defined as the target criterion. In addition, the software was instructed to stop the training process if the validation error increased. After 15,501 training cycles, the software achieved a training error of 0.001912 and a validation error of 0.030265; therefore, the training process was terminated after this number of cycles.

4 | Discussion of Findings

Fig. 9 shows the importance of each input parameter in the ANN model of the Stereolithography process. The term “importance” actually represents the sum of the weights of the connections linking the input layer to the intermediate hidden layer. In the MLP network developed in this study, there are a total of 35 connections between the input layer and the hidden layer. In addition, 21 connections link the intermediate hidden layer to the output layer.

As can be seen from *Fig. 9*, among the input parameters, the highest importance is attributed to layer thickness, with a total weight of 77.8247. This result is consistent with many findings reported in previous studies [15], [16].

Fig. 9. Relative importance of input parameters in the Stereolithography process.

The hatching method, based on the analysis of this network, ranks second in terms of importance, with a total weight of 59.2407. This finding is of great significance because, in many studies, by keeping the hatching method fixed as the Star-Weave method, insufficient attention has been paid to this fundamental parameter. The ANN analysis conducted in this study confirms the findings of Ono and Hong [5] and demonstrates that improving hatching methods can lead to a significant increase in the dimensional accuracy of parts fabricated using the SL process.

5 | Conclusion

The present study investigated the influence of hatching strategy on the dimensional accuracy of components fabricated by the Stereolithography (SLA) process. Different hatching approaches were reviewed, and the effect of hatching strategy was quantitatively evaluated through ANN modeling of the SLA process. Based on the obtained results, the following conclusions can be drawn:

Among the investigated process parameters, layer thickness was identified as the most influential parameter affecting the dimensional accuracy of SLA-fabricated parts. This finding is in agreement with previous experimental studies and confirms the dominant role of layer thickness in controlling curing behavior and dimensional deviations.

Hatching strategy was found to be the second most important parameter influencing dimensional accuracy. The ANN analysis demonstrated that the selection of an appropriate scanning pattern has a significant effect on reducing distortion and improving the dimensional stability of fabricated components. Therefore, hatching strategy should not be considered as a fixed machine parameter, but rather as an effective optimization variable in SLA process planning.

The analysis confirmed that advanced hatching strategies, such as DSW, DDSW, and Circular STAR-WEAVE methods, can improve dimensional accuracy by providing a more uniform distribution of curing shrinkage and residual stresses. In particular, reducing the length of hatch vectors and avoiding repetitive scanning paths can minimize directional shrinkage effects and improve the geometric accuracy of final parts.

The developed MLP artificial neural network successfully modeled the nonlinear relationship between SLA process parameters and dimensional distortion. The obtained low training error (0.001912) and acceptable validation error (0.030265) indicate that ANN models can be effectively employed as predictive tools for analyzing and optimizing RP processes.

The results emphasize the importance of considering scanning strategy as a key design parameter in SLA fabrication. By optimizing hatching patterns together with other process parameters, higher dimensional accuracy and improved quality of additively manufactured components can be achieved.

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