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Statistical analysis of the stereolithographic process to improve the accuracy

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Abstract

Stereolithography (SL) is a widely used technology in the field of rapid prototyping. However, the dimensional accuracy of SL products is today still limited; therefore, this technology needs to be optimized for high precision applications. This paper presents a statistical analysis of the stereolithographic process, in order to find out the combination of parameters leading to the best accuracy of the manufactured parts. A particular benchmark was designed and a global error index was introduced to evaluate the global distortion of built parts. The Taguchi methodology was employed for the optimization. A Viper Si_2 machine by 3D Systems was used in both the modalities allowed from this system: Normal and High Resolution.

Moreover, a detailed analysis of the resin polymerization mechanism was performed; from this study it emerged that the post-curing process is not always necessary if the process parameters are chosen for not having uncured areas.

Keywords: Stereolithography; Curing; Benchmark; Accuracy; Optimization

1. Introduction

Stereolithography (SL) is a photopolymerization process that uses a laser beam to selectively draw or print cross sections of a model on a photocurable resin surface [1].

The main feature of RP technologies is the selective creation of material, layer by layer, producing a part directly from CAD data. The CAD file is then converted into the STL format that is a faceted version of the surface of the model. Such a model is then "sliced" at distances equal to the layer thickness.

A laser generating a small, intense beam is moved by a computer-controlled optical scanning system across the top of a vat containing liquid resin. The laser draws each layer of the part from the data provided by the build data file. As the laser contacts the resin, the beam photopolymerizes the resin into a solid. When a layer is completed, an elevator lowers the part deeper into the vat, covering it with the resin contained in the vat. Levelling and recoating systems establish the thickness and flatness of the liquid layer. When the resin surface is stable, the laser draws the next layer of the part. As each layer is drawn, it adheres to the previous layer, creating a solid part. The platform then rises out of the liquid resin and the necessary clean up and post-curing is performed.

The machine used to build parts is called a stereolithography apparatus (SLA) [2].

Generally, during the photopolymerization process the resin does not reach full solidification; therefore, after building in the SLA, the part is put into an UV oven to be cured up to 100% and to complete the polymerization process (post-curing process). The machine used for the post-processing is called a Post-Curing Apparatus (PCA). However, under this process, the presence of shrinkage and distortion within the prototype is one of the major sources of error in the SL process.

Several studies have been performed to investigate the curing of photopolymers used in the SL process and the mechanisms of the resulting shrinkage [3–5]. The results were that post-treatment processes lead to the generation of polymerization shrinkage strains of considerable magnitude.

A high degree of dimensional accuracy is required for stereolithographic objects, especially for high precision applications, such as jewelry.

The objective of the present paper was to find out the process parameters optimising the dimensional accuracy of the SL technique without the need for post-processing.

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2. Photopolymerization

2.1. Analytic model

The solidification of the liquid resin depends on the energy per unit area (exposure) left from the laser beam on the surface of the photopolymer [6,2]. The expression of the volumetric exposure left from a laser beam scanning a photopolymer with a scan speed V_s and a laser power P_L is:

$$E(y,z) = \sqrt{\frac{2}{\pi}} \frac{P_L}{W_0 V_s} \exp\left(-\frac{2y^2}{W_0^2}\right) \exp\left(-\frac{z}{D_p}\right) \tag{1}$$

where y–z is the plane normal to the scanning plane x–y; the z axis is positively oriented with the internal part of the vat; D_p is the penetration depth of the resin; W_0 is the laser beam waist $-1/e^2$ half-width for a laser characterized by a Gaussian transversal modality.

Now it is possible to introduce the concept of critical exposure E_c, that is the value characteristic of each polymer, under which the resin remains in the liquid state during the laser interaction. Therefore, the polymerization is possible only when the exposure is greater than the critical value E_c, otherwise the resin remains liquid.

The intensity distribution is:

$$I(x,y) = I(r) = I_0 \exp\left(-\frac{2r^2}{W_0^2}\right). \tag{2}$$

The intensity distribution under the resin surface can be easily obtained by means the Lambert–Beer absorption:

$$I(x,y,z) = I(x,y) \exp\left(-\frac{z}{D_p}\right). \tag{3}$$

The laser radiation is characterized by wavelength λ and power P_L.

So, finally, from Eq. (1), when an actinic Gaussian laser beam at constant speed V_s crosses a photopolymer following the Beer–Lambert law, it produces a single cured line with the shape of a parabolic cylinder characterized by a maximum cure depth C_d and a width L_w (Fig. 1). The maximum exposure is:

$$E_{\max} = \sqrt{\frac{2}{\pi}} \cdot \left[\frac{P_L}{W_0 \cdot V_s}\right]. \tag{4}$$

The maximum exposure $E_{\max}$ is related to the cure depth with the following equation

$$C_d = D_p \ln\left(\frac{E_{\max}}{E_c}\right). \tag{5}$$

This is an important equation for the SL process and it's called the working curve of the laser. D_p and E_c are parameters dependent only from the resin, so it is possible to calculate the maximum exposure that is necessary to generate a cure depth C_d. It is also possible to calculate the maximum cured line width L_w by the expression:

$$L_w = B\sqrt{\frac{C_d}{2D_p}} \tag{6}$$

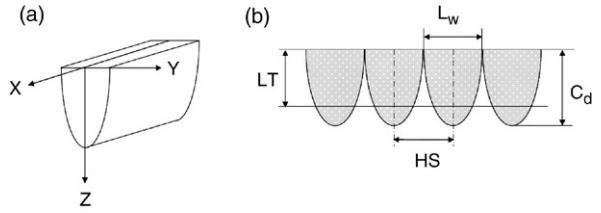

Fig. 1. (a) Parabolic cylinder shape of the cured line; (b) cross-sectional view of cured lines.

Table 1
RP Cure 400 ND properties

	Method	
D_p (mils)	Window-panes	5.5
E_c (mJ/cm^2)	Window-panes	11.9
Liquid resin viscosity at 30 °C (cps)	Brookfield	483

Table 2
Laser spot diameter values for Viper Si_2

Modality	B (@$1/e^2$) (mm)
Normal resolution (NR)	0.250 +/− 0.025
High resolution (HR)	0.075 +/− 0.015

where $B = 2\ W_0$ is the laser spot diameter [7].

2.2. The present analysis

The resin used in the present work was RP Cure 400 ND. Table 1 shows D_p and E_c values for this resin.

The machine used to build parts was a Viper Si_2 machine by 3D systems.

B is a characteristic of the Viper Si_2 machine, which is equipped with a solid state laser Nd:YVO4 with a wavelength of 354.7 nm and a maximum power of 100 mW. Viper Si_2 can work in two modalities: normal resolution (NR) and high resolution (HR), characterized respectively by a layer thickness of 0.1 and 0.05 mm. Table 2 shows the values of B for the two modalities.

2.3. Process parameters

The parameters considered in this analysis were: layer thickness, hatch overcure, hatch spacing, border overcure, fill spacing and fill cure depth. Layer thickness is the depth of a layer that is determined by the stepping of the elevator in the same increments. This converts the two dimensional cross sections into three dimensional layers of the actual prototype. Hatch spacing (HS) is the distance between a couple of adjacent vectors, where a vector means the narrow region solidified by the laser scanner. If the vector is located on the bottom surface of the part the spacing is called fill spacing. Cure depth is the depth of vectors. If the vector is located on the top or bottom surface of the part it is called fill cure depth. Overcure is the penetration depth of a vector in the lower adjacent layer, if it is located in the internal region of the part it is called hatch overcure (HO), while if it is located at the lateral boundaries it is called border overcure (BO) [8].