Photopolymer Solidification for Inclined Laser Exposure Conditions

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Abstract

It has been reported that the photopolymer solidification in the stereolithogrpahy process is mainly depended on the laser exposure conditions such as laser power and scanning speed. However, they were focused on the vertical laser exposure conditions. In this research, we developed a mathematical model for the photopolymer solidification under the inclined laser beam exposure condition. Using the developed mathematical model, the photopolymer solidifications were simulated for various inclined laser exposure conditions. Developed mathematical model was in good agreement with the experimental result. This research can be applied to improve the surface roughness in the stereolithogrpahy process.

Introduction

The stereolithography process is a layer-by-layer manufacturing process which cures the photopolymer by UV laser beam. In this process, for the solidification of the photopolymer, various factors have to be considered such as laser power, laser irradiation speed and material properties of the photopolymer[1].

Most of previous studies on the photopolymer solidification were mainly focused on the perpendicular irradiation of the laser beam on the surface of the photopolymer[2~4].However, when the laser beam irradiates with an inclined angle, it is difficult to apply these results directly. In this study, the photopolymer solidification was examined theoretically and experimentally when the UV laser beam has an inclined angle.

Mathematical Model

Irradiance distribution of TEM_{00} mode laser beam is Gaussian distribution. As shown in Fig. 1, if coordinates of a plane perpendicular to the beam axis is x, y, irradicance distribution of laser beam on the surface of photopolymer becomes Eq.(1).

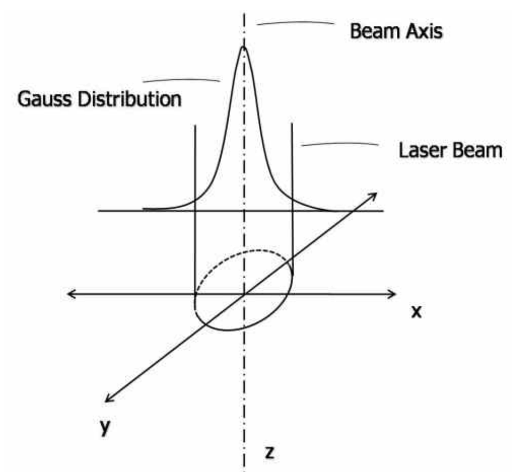


Fig. 1 Gaussian distribution of laser beam

$$H(x,y) = H_0 \cdot \exp\left(-2\frac{x^2}{w_0^{\ 2}}\right) \cdot \exp\left(-2\frac{y^2}{w_0^{\ 2}}\right) \tag{1}$$

Where, H_0 = Maximum irradiance of the laser beam, w_0 = Gaussian half width of laser beam. According to the Beer-Lambert Law, the irradiance of laser beam in the photopolymer is reduced exponentially (Eq.(2)).

$$H(z) = H_0 \cdot \exp\left(-\frac{z}{D_P}\right) \tag{2}$$

Where, D_P = Penetration depth of the photo polymer at given wavelength. Therefore, using Eq.(1) and Eq.(2), irradiance in the photopolymer along the z-axis is expressed as Eq.(3)[5].

$$H(x,y,z) = H_0 \cdot \exp\left(-2\frac{x^2}{w_0^{\ 2}}\right) \cdot \exp\left(-2\frac{y^2}{w_0^{\ 2}}\right) \exp\left(-\frac{z}{D_P}\right) \tag{3}$$

Fig.2 shows UV laser beam irradiates on the photopolymer having inclined angle θ. In Fig. 2, distances from the optical axis and the surface of the photopolymer along the optical axis to a point $a(y_0, z_0)$ in the photopolymer can be expressed as Eq.(4) and Eq.(5), respectively.

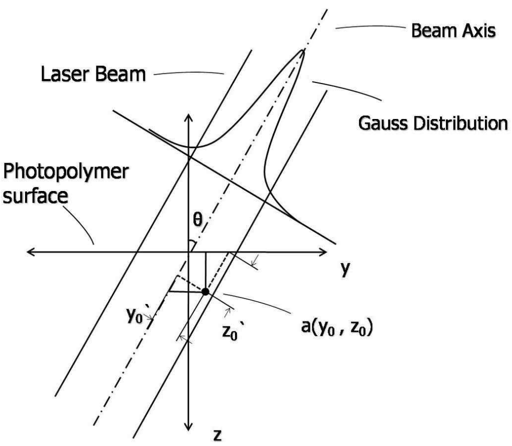


Fig. 2 Inclined exposure with θ

$$y_0` = y_0 + z\tan\theta \tag{4}$$

$$z_0` = \frac{z}{\cos\theta} \tag{5}$$

Therefore, by using Eqs.(3), (4) and (5), the irradiance in the photopolymer when the laser beam has an inclined angle θ can be expressed as Eq.(6).

$$H(x,y,z) = H_0 \cdot \exp\left[-2\frac{(z\sin\theta + y\cos\theta)^2}{w_0^{\;2}}\right] \cdot \exp\left(-\frac{z}{D_P\cos\theta}\right) \cdot \exp\left(-2\frac{x^2}{w_0^{\;2}}\right) \tag{6}$$

On one hand, the irradiance distribution of TEM_{00} mode laser light on the surface of photopolymer is expressed as Eq(7). Therefore by integrating Eq.(7) the laser power P_L can be obtained as Eq.(8)

$$H(r,0) = H_0 \cdot \exp\left(-2\frac{r^2}{w_0^{\;2}}\right) \tag{7}$$

$$\begin{aligned} P_L &= \int_{r=0}^{r=\infty} H(r,0)dA \\ &= \frac{\pi w_0^{\;2}}{2} H_0 \end{aligned} \tag{8}$$

Substituting Eq.(8) into Eq.(6), Eq.(9) is obtained. Eq(9) expresses the irradiance at a point in the photopolymer when the inclined laser beam with angle θ irradiates on the surface of the photopolymer.

$$H(x,y,z) = \frac{2}{\pi w_0} P_L \exp\left[-\frac{2(z\sin\theta + y\cos\theta)^2}{w_0^{\;2}}\right] \cdot \exp\left(-\frac{z}{D_P\cos\theta}\right) \cdot \exp\left(-2\frac{x^2}{w_0^{\;2}}\right) \tag{9}$$

If laser beam irradiates along the x axis at the speed of V_S, then exposure(E) at a point on the surface of photopolymer can be expressed as the integration of laser irradiance on the surface of photopolymer as shown in Eq(10).

$$E(x,y,0) = \int_{t=-\infty}^{t=\infty} H[x(t), y(t), 0]dt \tag{10}$$

Introducing V_S=dx/dt and the Gauss error function, Eq.(10) is expresses as Eq.(11).

$$E(y,0) = \sqrt{\frac{2}{\pi}} \frac{P_L}{w_0 V_S} \exp\left[-\frac{2(y\cos\theta)^2}{w_0^{\;2}}\right] \tag{11}$$

Therefore, according to the basis of Beer-Lambert law, exposure in the photopolymer can be expressed as Eq.(12).

$$E(y,z) = \sqrt{\frac{2}{\pi}} \frac{P_L}{w_0 V_S} \exp\left[-\frac{2(z\sin\theta + y\cos\theta)^2}{w_0^{\;2}}\right] \exp\left(-\frac{z}{D_P\cos\theta}\right) \tag{12}$$

In the stereolithography process, boundary surface can be exist in gel state when photopolymer is cured by laser beam. Let y and z coordinates of this state are y* and z*, then exposure on this point becomes Critical Exposure(Ec). Accordingly, Eq.(12) can be rearranged as Eq.(13).

$$\frac{2}{w_0^{\ 2}}(z^* \sin\theta + y^* \cos\theta)^2 + \frac{1}{D_P \cos\theta} z^* = \ln\left(\sqrt{\frac{2}{\pi}} \frac{P_L}{w_0 V_S E_C}\right) \tag{13}$$

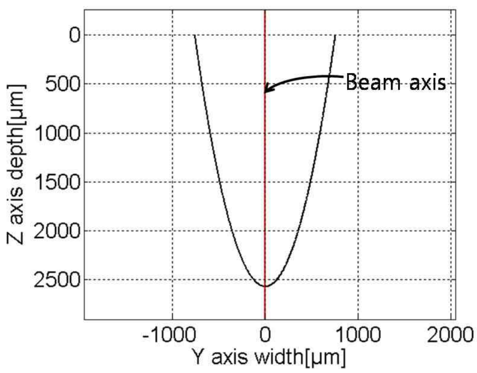
Eq.(13) expresses the cured shape of photopolymer on y-z plane when laser beam irradiates on photopolymer with inclined angle θ.

Simulation

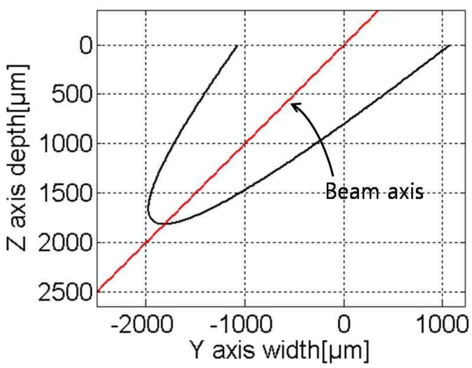
Using developed numerical model, computer simulation were performed. Simulation paramerers are shown in Table 1.

Table 1 Simulation parameters

P_L(μW)	100
w_0(μm)	250
V_S(mm/min)	1.8
E_C(mJ/cm2)	11.5
D_P(mm)	0.14



(a)



(b)

Fig. 3 Photopolymer solidification simulation result (y, z) considering θ;
(a) θ=0° and (b) θ=45°

Fig. 3(a) and (b) show the cured photopolymer shape projected on y-z plane when laser beam is irradiated at 0° and 45° angle, respectively. As shown in Fig. 3, if laser beam irradiates on the photopolymer with inclined angle, then the cure shape of photopolymer is changed along the beam axis.

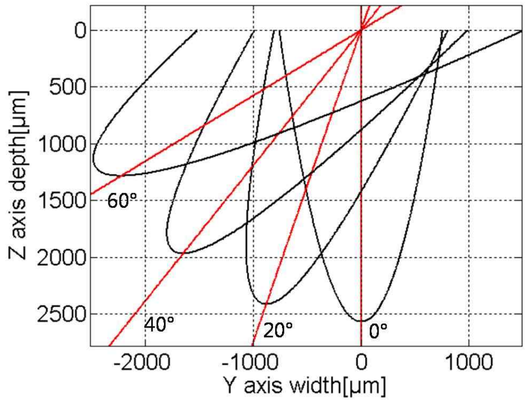


Fig. 4 Photopolymer solidification simulation result (θ=0°~60°)

Fig. 4 shows shapes of curedphotopolymer when incidence angle of laser beam changes (0°~60°). As shown in Fig. 4, the cured shape of photopolymer is changed along the beam axis when the incline angle changes. From this result, it was found that it is possible to fabricate a shape which has better surface roughness than conventional stereolithography[6].

Inclined Exposure Experiments

Fig. 5 shows schematic drawing of experimental appartus. Laser beam from UV laser is irradiated on the photopolymer at designated incline angle. Incline angle is controlled with rotation stage equipped with UV mirror. The UV laser beam has Gaussian half-width of 250μm and wavelength of 375nm. WaterShed11110 was used as photopolymer. The experiment was performed with inclination angle of 45° under the condition of P_L=96μW, V_S=1.8mm/min.

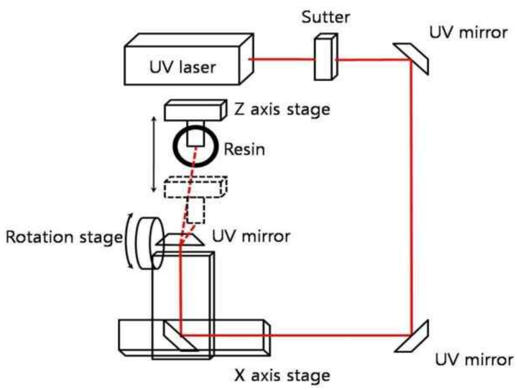


Fig. 5 Schematic drawing of experiment apparatus

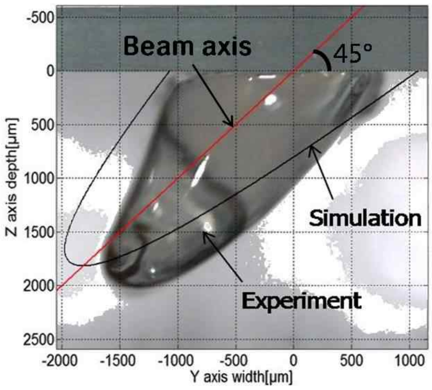


Fig. 6 Experiment result at θ=45°

As shown in Fig.6 the simulated shape of cured photopolymer is in good agreement with experimental result. However, the inclination is slightly different. This is because the refractive index of the photopolymer was not considered in the numerical model. Further study will be conducted to improve accuracy of numerical model

conclusion

The photopolymer solidification in the stereolithography process for the inclined laser exposure was studied. From this research the mathematical model was developed. Experimental result is in good agreement with the simulation result by the mathematical model. Further study will be conducted to improve accuracy of the numerical model.

Acknowledgments

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