Theoretical and experimental research on the coating process of ceramic stereolithography

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Abstract- The coating process in ceramic stereolithography is one of the principal sources of inaccuracy in the height dimension. The coating in stereolithography is a layer-by-layer build-up process, so the thickness of one layer coated is influenced by the previous layer and affects the thickness of the next layer. If inconsistent layer thicknesses exist, they will result in the poor quality of the final product. This paper analyzes the coating process of the slurry-separated system based on a simple 2D model and Navier-Stokes equations, presenting the theoretical equations of layer thickness for the commonly used blade types. Given the characteristics of layer-by-layer coating in stereolithography, the theoretical equations should be constantly iterated to obtain the thickness of each layer. This paper discovers the initial blade gap has a significant impact on the layer thicknesses by theoretical analyses. With the verification of experiments, the results show that the presence of the unreasonable initial blade gap may lead to large fluctuations in layer thicknesses of the first few layers, and the coating in stereolithography is a "self-regulating" process with a tendency to the desired thickness. The larger the desired layer thickness, the worse this "self-regulating ability" is. This paper defines a coefficient of blade gap and proposes that using the coefficient of blade gap to determine a reasonable initial blade gap based on different working conditions can effectively control the consistency of each layer thickness.

1. Introduction
Additive manufacturing technology is based on the principle of discrete-three-dimensional stacking processing, incorporating computer-aided design, material processing, and three-dimensional forming technology. There are many additive manufacturing technologies such as Laminated Object Manufacturing (LOM), Stereolithography Apparatus (SLA), Selected Laser Sintering (SLS), direct ink writing (DIW), Ink Jet Process (IJP). Among them, SLA is the most advantageous in additive manufacturing of ceramic pastes due to the high precision, high forming quality, and large dimensions of ceramic products. Stereolithography of ceramic pastes is a layer-by-layer process, where a layer of ceramic paste is cured and another layer of ceramic paste should be precisely coated on the surface of
the cured layer to make the process continuous. The coating process is one of the key factors affecting the quality of stereolithography. Due to the high viscosity of the ceramic slurry, the light source top-mounted ceramic coating systems mostly use blades, and the commonly used blades are mainly divided into straight blades, beveled blades, and combined blades.

Few studies have been conducted for the stereolithography coating process. K. Renap\cite{1} studied the relationship between resin layer thickness and recoating process parameters by simulating the recoating process of the SL system and concluded that the recoating process parameters should be optimized to ensure the accuracy of the prototype part. Zhao\cite{2} studied the relationship between resin layer thickness and recoating process parameters for the waterfall recoating system. Pham\cite{3} studied the coating process for parts containing cavities, concluded that different speeds need to be matched for different cavity depths, and investigated other recoating parameters to obtain excellent recoat quality. The high-resolution SL system developed by the Institute of Advanced Manufacturing Technology of Xi’an Jiaotong University used a piston-type recoating system\cite{4, 5}, the researchers found that the thickness of the resin layer increased as the height of the solidified layer increased. Xu\cite{6} used the response surface approach to establish the relationship between the thickness of the resin layer, the height of products, and the speed of blades to solve this problem. Based on this relationship, the researchers proposed a theory for the dynamic optimization of speed in the manufacturing process.

In the above-mentioned studies, the researchers have mostly studied the resin material and the theoretical derivation only considers the straight blade. More attention is paid to the case of a single layer of coating and less to the variation of thicknesses\cite{7, 8}. The coating in stereolithography is a layer-by-layer process and the adjacent layers can affect each other. The inconsistency in layer thicknesses can affect the height dimension of the part, so it is necessary to research the changes in layer thicknesses.

We first present the development of the numerical model in Section 2, which is based on a 2D model and Navier-Stokes equations. In Section 3, we give the experimental details to investigate the relationship between the initial blade gap and actual layer thicknesses. The experimental and theoretical results are then introduced in Section 4.

2. Theoretical modelling of the slurry-separated system

The stereolithography coating system studied in this paper is a slurry-separated system\cite{9}, which is different from the previous research systems\cite{2-6, 10, 11} and the coating process is shown in Fig.1. The entire coating process can be briefly divided into four steps: (1) The supply system pushes the slurry out (Fig.1(a)); (2) Coating, the blade evenly coats the slurry supplied over the working area (Fig.1(b)); (3) The laser cures the ceramic slurry by surface exposure according to the cross-sectional pattern provided by the software (Fig.1(c)); (4) The platform is lowered a desired thickness in for the next coating (Fig.1(d)).

![Fig.1 The printing process in the slurry-separated system.](image)

In order to describe the coating process, we need to simplify the stereolithography coating process into a two-dimensional model, as shown in Fig.2. This simplification is reasonable as far as the printing geometry is uniform and the blade is long in the direction perpendicular to the blade motion.
Fig.2 Two-dimensional diagram of the stereolithography coating process. (L: the width of the blade, d: layer thickness, H(0): the thickness of slurry outlet, also called blade gap, H(L): the thickness of slurry inlet, H(x): the thickness at any x position, h0: the height of the accumulated slurry.)

To simplify the research process, some assumptions should be considered: 1. In the actual coating process, the width of the blade is much larger than the blade gap (L >> H(0)), so the flow of the fluid in this model can be considered as steady-state flow. 2. According to the parameter range of the actual coating process (the maximum value of H(x) ≈ 20 mm, noted that H(0) ≤ 0.3 mm, Uc = 20~50 mm/s, the dynamic viscosity of the slurry h ≈ 10 pa·s and the density of the slurry r ≈ 4 g/cm³, the Reynolds number turns out to be Re = rUcH(x)/h ≲ 1), it represents the adhesive force dominates, so we can neglect the inertial force. 4. Because the high shear rate (t = Uc/H(0)) is high, the Non-Newtonian phenomena of the ceramic slurry are not evident [8]. We assume that the viscosity of the ceramic slurry remains constant during the coating process. Based on the above assumptions, the Navier-Stokes equations, Eq. (1) can be simplified to Eq. (2), where P is the pressure in the flow path.

\[
\rho \left( \frac{\partial U}{\partial t} + U \cdot \nabla U \right) = \nabla P + \rho g + \eta \nabla^2 U
\] (1)

\[
\frac{dP}{dx} = \frac{d}{dy} \left( \eta \frac{dU}{dy} \right)
\] (2)

In the actual coating process, the blade moves, and the cured layer is fixed. For simplicity of calculation, we assume the blade is fixed and the cured layer moves with a velocity of Uc in the opposite direction. The shape of the blade bottom surface is set to y = H(x), Eq. (2) satisfies the boundary conditions: y = 0, U = Uc, and y = H(x), U = 0. Thus, Eq. (3) is obtained.

\[
U = \frac{1}{2\mu} \frac{dp}{dx} y^2 - \left( \frac{U_c}{H(x)} + \frac{1}{2\mu} \frac{dp}{dx} H(x) \right) y + U_c
\] (3)

The unit flow rate at an arbitrary section can be expressed by Eq. (4).

\[
q = \int_0^{H(x)} U dy = \frac{1}{2} U_c H(x) - \frac{1}{12\mu} \frac{dp}{dx} H^3(x)
\] (4)

For any section, dp = ρgh₀ − P(x). When x = L, because δ is very small compared with h₀, we assume P(L) ≈ 0, According to δ = qUc, the thickness at the outlet can be obtained, Eq (5).

\[
\delta = \frac{\rho gh_0}{12\mu U_c} \int_0^L \frac{1}{H^2(x)} dx + \frac{1}{2} \int_0^L \frac{1}{H^3(x)} dx
\] (5)

In the common equipment of the stereolithography coating system, the conventional blade meets the condition that the blade width is much larger than the blade gap [12], so we only need to correctly determine the expression of H(x) to calculate the theoretical thickness values. This paper lists the theoretical thickness formulae for coating under commonly used blade types, including straight blade seen in Fig.3(a), beveled blade seen in Fig.3(b), and combined blade seen in Fig.3(c). The expressions for theoretical thicknesses are shown in Table 1.
(a) Straight blade                   (b) Beveled blade              (c) Combined blade

Fig.3 The blades commonly used for stereolithography coating systems. (b: blade gap, L: the width of the blade. m: the length of the straight blade part of the beveled blade surface. \( \theta \): the angle of the beveled blade.)

Table 1 Theoretical derivation for different blade types during the stereolithography coating process

| Blade Type          | Formula                                                                 |
|---------------------|-------------------------------------------------------------------------|
| Straight blade      | \( H(x) = b \)                                                         |
|                     | \( \delta = \frac{b^3 \rho g h_0}{12 U_c L \mu} + \frac{b}{2} \)        |
| Beveled blade       | \( H(x) = b + x \tan \theta \)                                         |
|                     | \( \delta = \frac{\rho g h_0 b^2 (b + L \tan \theta)^2 + 6 \mu L b U_c (b + L \tan \theta)}{6 \mu L b U_c (2b + L \tan \theta)} \) |
| Combined blade      | \( H(x) \)                                                             |
|                     | \( k_1 = \frac{m}{b^2} - \frac{1}{\tan \theta} \left( \frac{1}{b + L \tan \theta} - \frac{1}{b + m \tan \theta} \right) \) |
|                     | \( k_2 = \frac{m}{b^3} - \frac{2 \tan \theta}{1} \left( \frac{1}{(c + L \tan \theta)^2} - \frac{1}{(c + m \tan \theta)^2} \right) \) |
|                     | \( \delta = \frac{\rho g h_0}{12 U_c L \mu k_1} + \frac{k_1}{2k_2} \) |

The desired layer thickness \( h_d \) and the initial blade gap \( b_1 \) should be set before printing. It is noted that the first actual layer thickness is related with \( b_1 \), not with \( h_d \) because the platform is at the initial point in this printer. In the initial case, \( b=b_1 \). The actual coating process in a slurry-separated system is a layer-by-layer process as follows: 1. Coat the first layer and set the actual thickness obtained as \( d_1 \). 2. After curing, the platform drops down by a desired layer thickness \( h_d \), waiting for the next coating. At this point the blade gap \( b \) is \( b_1+h_d-d_1 \). 3. Coat the second layer and set the thickness obtained as \( d_2 \). 4. After curing, the platform drops down by a layer thickness \( h_d \) again. At this point, the blade gap \( b \) is \( b_1+2h_d-d_1-d_2 \). And in a similar fashion, the processes go on until the end of the print. (\( b \) is the value of \( H(0) \) in Fig.2)

From the above analysis, we can see that each layer is coated with a different blade gap, which is affected by the previous layer thickness, so if we want to obtain the layer thickness of each layer, we need to continuously update the value of \( b \) and iterate on the theoretical formula. Though \( h_0 \) are not constant in the coating process, the variation in \( h_0 \) has little effect on \( dp \) where \( \rho \) plays a leading role. Thus, we assume \( h_0 \) is constant for simplicity.

In this paper, we use the combined blade, which defined parameters are \( q=75^\circ \), \( m=0.4 \), \( L=7.4 \). Other parameters including \( c \), \( k_1 \), and \( k_2 \) vary with \( b \). The thickness calculations of a single layer coated by this blade are shown in Fig.4 showing that the higher the viscosity and the faster the speed, the layer thickness coated is slightly more than half the blade gap, i.e. \( d \approx b/2 \).
The initial blade gap is an independent parameter that needs to be adjusted manually. If the initial blade gap is not adjusted properly, the first actual layer thickness will deviate from the desired layer thickness and will affect the subsequent layer thicknesses. We experimentally investigated this influence in Section 3.

3. Experiment

This experiment was carried out using alumina paste as the raw material, and the experimental system is the laboratory’s own stereolithography printing platform Basic 1.0, shown in Fig.5. The material and experimental parameters are shown in Table 2.

![Fig.5 The printing system in this experiment, Basic 1.0.](image)

| Material                 | Alumina slurry          |
|--------------------------|-------------------------|
| Viscosity \( m_{\text{Alumina}} \) | 10 Pa·s (the shear rate \( \tau > 200\text{s}^{-1} \)) |
| Density \( \rho_{\text{Alumina}} \) | 4.0×10³ kg/m³          |
| Coating velocity \( U_c \) | 30 mm/s                 |
| Exposure power           | 12 w                    |
| Exposure time            | 5 s                     |
| Height of paste build-up in front of knife \( h_0 \) | 15.2 mm          |

According to the analysis of the coating process in Section 2, the stereolithography coating process is a layer-by-layer process. The initial blade gap is crucial for subsequent layer thicknesses. Due to the high viscosity of the slurry and the high velocity, the first layer thickness is \( d_1 \approx b_1/2 \). The relationships between the initial blade gap and the desired layer thickness \( h_d \) can be divided into three situations: \( d_1 > h_d, d_1 < h_d, d_1 = h_d \). Based on the relationships and printing devices, \( b_1 \) and \( h_d \) were designed in Table 3.
Table 3 The values of $b_1$ and $h_d$ in three experiments.

| Experiment number | Initial blade gap $b_1$ (μm) | Desired layer thickness $h_d$ (μm) |
|-------------------|------------------------------|----------------------------------|
| 1                 | 200                          | 50                               |
| 2                 | 100                          | 100                              |
| 3                 | 100                          | 50                               |

The actual experimental process is as follows: 1. Lay a finely printed paper on the printing platform to facilitate the removal of the print material from the platform. 2. Use the gauge to adjust the distance between the blade and the paper. The distance is considered as blade gap $b_1$. 3. Set the desired layer thickness and other experimental parameters to print the parts. The model of the part (length×width×height: 30 mm×10 mm×1 mm) is shown in Fig.6. Each experiment prints three parts. 4. Use the microscope to obtain each layer thickness, Fig.7.

4. Results
The results of experimental measurements and the theoretical calculations are shown in Fig.8. Each experimental data was obtained by measuring three parts and taking the average of the three results. Each theoretical data was obtained by iterating the theoretical formula. Fig.8 shows that the relationship between the initial blade gap and the layer thicknesses greatly influences the fluctuations in coating thicknesses, especially in the first few layers. When the blade gap is not set appropriately ($d_i > h_d$ or $d_i < h_d$), it will cause drastic changes among the layer thicknesses. As can be seen from Fig.8 (a), if the first layer thickness is larger than the desired layer thickness ($d_1 > h_d$), the subsequent layer thickness gradually will decrease to the desired layer thickness and then fluctuate slightly around the desired layer thickness. As can be seen from Fig.8 (b), if the first layer thickness is smaller than the desired layer thickness ($d_1 < h_d$), the subsequent layer thicknesses will gradually increase to the desired layer thickness and then fluctuate slightly around the desired layer thickness. As can be seen from (c), if the first layer thickness is near the desired layer thickness, then the subsequent layer thicknesses will not drastically fluctuate and will ensure that the error of height direction is small due to the consistency of the layer thicknesses.

![Fig.6 Printed model in experiments.](image1)

![Fig.7 The image observed by the microscope.](image2)

![Fig. 8 Graphs of theoretical and experimental results.](image3)
By defining the error of each layer as the difference between the experiment data and the theoretical data, the relative error of each layer can be defined as the ratio of the absolute value of the error to the theoretical data. The relative error of each layer is shown in Table 4. It can be seen from Table 4 that most relative errors are less than 10%, and the maximum of the relative errors is only 21%. Most of the large errors occurred in Experiment 1, and was likely to be a result of the large error in adjusting the initial blade gap. Excluding random errors, relative errors may arise for the following reasons: (1). The viscosity of the slurry and the height of the slurry in front of the blade vary slightly during the process. (2). The mechanical systems may produce errors, such as the height at which the platform is lowered. According to the relative errors and the above analysis, the relative errors are within a reasonable range, and the experimental and theoretical data are well fitted. They prove the theoretical formulas can reasonably predict the trend and values of the layer thicknesses, which can provide theoretical guidance for subsequent research.

Table 4 The relative errors. (unit: %)

| Number of | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Experim.  |     |     |     |     |     |     |     |     |     |     |
| number 1  | 19.8| 5.5 | 21.0| 19.8| 11.5| 9.6 | 0.7 | 12.7| 0.7 | 3.9 |
| number 2  | 3.6 | 2.6 | 7.4 | 2.1 | 12.3| 2.0 | 4.5 | 2.3 | 1.2 | 9.0 |
| number 3  | 1.4 | 3.1 | 8.5 | 5.7 | 6.1 | 11.4| 1.8 | 2.6 | 6.9 | 0.1 |

Applying theoretical formulas to predict the influence of different initial blade gaps on fluctuations in layer thicknesses, as shown in Fig.8. Define the initial-layer error as the difference between the actual first layer thickness and the desired layer thickness. It shows that the larger the desired layer thickness, the more significant the fluctuations in layer thicknesses, the less ability of "self-regulating" in the layer-by-layer coating, and the bigger the number of cured layers to reach the desired layered thickness for the same initial-layer error.

![Fig.9 The fluctuations in layer thicknesses at different blade gaps $b_i$.](image)

(a) The desired layer thickness $h_d=0.05$ mm (b) The desired layer thickness $h_d=0.1$ mm

As can be seen from the analysis of the above, if the initial blade gap can be set reasonably before printing, the fluctuations in layer thicknesses will be small in the whole stereolithography coating process, which is important for the accuracy in the height direction. Based on the theoretical formulas in the coating process of the combined blade, this paper defines $k_0 = \frac{rgh_0}{12Ucm}$, which is called the blade gap coefficient. This coefficient is determined by the material density, material viscosity, blade velocity, and pressure difference. The blade gap coefficient $k_0$ is different for different working conditions. For a defined blade type, an optimum blade gap can be determined by $k_0$ and the desired layer thickness. This paper gives the line diagrams of $k_0$ for the Basic1.0 system, Fig.10.
5. Conclusion
The 3D printing stereolithography coating process is a layer-by-layer coating process. The present study focuses on the influence of the initial blade gap on layer thicknesses in the coating process through theoretical analyses and experiments.

1. The simplified coating model in the slurry-separated was established to derive the layer thickness for different blade types (straight blade, beveled blade, and combined blade). This paper proposes that only by iterating the thickness expressions can the theoretical thickness of a particular layer be obtained.

2. The theoretical and experimental results showed that the stereolithography coating process in the slurry-separated system is a “self-regulating” process with a tendency to the desired layer thickness.

3. This paper proposes using the blade gap coefficient \( k_0 \) to set the initial blade gap and obtain the accuracy in the height dimension for the Basic 1.0 printing system.

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