Research Article

Application of Digital 3D Printing Technology in Ceramic Art Creation

Mian Wang, Xinyu Zhao, and Dan Sun

Lu Xun Academy of Fine Arts, Shenyang 110004, Liaoning, China

Correspondence should be addressed to Dan Sun; sundan@lumei.edu.cn

Received 25 February 2022; Revised 5 April 2022; Accepted 11 April 2022; Published 21 April 2022

Academic Editor: Muhammad Usman

Copyright © 2022 Mian Wang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

3D printing technology is a modern technical means and process based on three-dimensional molding, digital manufacturing, reverse engineering, and other emerging fields. 3D printing ceramics is one of the diversified designs of modern ceramics. At the same time, with the development of 5G technology, the platform access method will make 3D printing easier and more common. The purpose of this paper is to study the printing, preparation, and sintering processes of ceramic materials based on 3D printing technology and realize the rapid prototyping of ceramic parts, which can meet the requirements of low-cost, single-piece, and small-batch processing. This paper proposes to focus on the research on materials, design methods, and technological processes suitable for ceramic 3D printing technology from the perspective of the integration of art and science. By using 3D printing technology to perform geometric functions, mixing, recombination, and other cutting-edge tasks, the composite design of works is enhanced. The experimental results show that in the high temperature sintering stage, 1600 °C is the holding temperature, the heating rate is 0.5 °C/min, and the holding time is 600 min, and the sintering effect of ceramic parts is better. The measured shrinkage rate of the ceramic sample does not exceed 16%, the porosity is 47%, the bulk density is 2.27 g/cm³, and the density is 53.2%. The results show that the ceramic parts prepared by this process can meet the basic performance requirements.

1. Introduction

As an engineering material, the history of ceramics can be traced back to BC. People mixed clay, sand, and water, kneaded them into specific shapes, and fired them to obtain original ceramic products. After the Industrial Revolution, ceramic materials began to be used in electric power, machinery, and other fields because of their excellent insulation and heat insulation. Since the 20th century, with the emergence of special ceramics, piezoelectric ceramics, and bioceramics, ceramic materials have become another popular material after metals and polymer materials. They are widely used in machinery, aerospace, medicine, electronics, and many other fields. The traditional production process of ceramics is divided into three stages: batching, molding, and firing. In the molding process, injection molding and rolling are the main methods. These two methods require high-precision molds to assist ceramic molding, and the processing of the mold itself is very complicated. This leads to a long production cycle, low production efficiency, and a low yield of traditional ceramics. In addition, due to the existence of the mold, it cannot achieve low-cost, single-piece, and small-batch processing, and it is difficult to meet the processing requirements of modern ceramics.

The 3D printing technology developed in recent years is different from the method of “subtraction” used in the traditional processing technology. Instead, it starts from nothing and uses the form of adding materials to accumulate objects layer by layer. The processing speed is fast, and the production cost is low. For processing parts with complex structures, such as hollowing out and complex heterossexual structures, 3D printing technology is far superior to traditional processing techniques. Therefore, using 3D printing technology to process ceramic materials can not only solve the problem of the long processing cycle of ceramic products but also use its technical characteristics to produce special structural ceramics that cannot be obtained by traditional processing technology. It has broad market application prospects and practical value.

The innovations of this paper are as follows: (1) This paper analyzes and compares different surface-forming
processes. Based on the constrained liquid surface method, this paper designs and builds a prototype of surface molding ceramic printing, which solves the problem of coating and printing high-viscosity ceramic paste. At the same time, this paper completes the construction and debugging of the control system of the experimental prototype and uses photosensitive resin for printing tests. (2) In this paper, the sintering temperature curve suitable for ceramic parts is given, and the changes in the components of ceramic parts during the sintering process are analyzed. The influence of sintering temperature on the density and sintering shrinkage of the parts is analyzed, and finally, ceramic parts that can meet the basic performance requirements are obtained.

2. Related Work

Bone has a strong self-healing ability, but bone defects that exceed a certain critical size will not heal themselves and require intervention to achieve complete healing. Mishra A characterized the material properties of 3D-printed apatite scaffolds, which were then tested in situ implantation of horse tubers in vivo for 6 months [1]. While this type of implant has been extensively tested in vitro, there are limited in vivo data and even fewer in relevant large animal models. Sing et al. aimed to review additive manufacturing processes for ceramic materials, focusing on the partial and complete melting of ceramic powders by high-energy laser beams without the use of binders. They first introduced selective laser sintering or melting (SLS/SLM) technology. They then analyzed the results of silica (SiO2), zirconia (ZrO2), and ceramic-reinforced metal matrix composites processed by direct laser sintering and fusion. In the current state of technology, it remains a challenge for them to directly use SLS/SLM to fabricate dense ceramic components. They discussed the key challenges encountered in the direct laser melting of ceramics. They include the deposition of ceramic powder layers, the interaction between the laser and powder particles, the dynamic melting and consolidation mechanisms of the process, and the presence of residual stresses in ceramics processed by SLS/SLM [2]. Despite the challenges, SLS/SLM has potential in ceramic manufacturing. Today, 3D printing with ceramics is a promising direction for the development of additive technology. Dolgin et al. developed an alumina- and wax-based ceramic paste printing technique. They modeled and manufactured a ceramic paste printing extruder, selected the composition of the paste, made a paste for printing, and sintered it. It measured the sintering parameters and physical and mechanical properties of the product and used a scanning electron microscope to study the microstructure of the printed product [3]. The purpose of Rölling’s study was to examine the perceptions of wearable accessory designers using 3D printing (3DP) technology. He conducted 16 semistructured interviews with 3DP wearable accessory designers around the world. The findings show that 3DP is easier than traditional production methods. Plastics are the easiest materials to print on, while steel and ceramics are harder to print. His research supported learning-friendly 3DP educational programs, software programs, and materials, educational resources needed in materials, and the creation of affordable higher quality printers [4]. Yang et al. introduced the preparation method, development status, and application fields of ceramic 3D printing. They reviewed recent advances in direct 3D printing and stereolithography of oxide (Al2O3, ZrO2) and nonoxide (Si3N4, SiC) ceramic suspensions. He demonstrated the influence of the molding method on the properties of ceramics and gave an outlook on the development of 3D printing [5]. Xlab et al. synthesized a UV-curable ZrO2-Al2O3 composite ceramic slurry based on SLA-3D printing technology and 3D printed the corresponding ceramic green body. He finally made ZrO2-Al2O3 composite ceramic parts through subsequent degreasing processes. At a sintering temperature of 1500 °C and a holding time of 60 min, the actual density, hardness, and fracture toughness of the ceramics can reach 3.75 g/cm, 14.1 GPa, and 4.05 MPam1/2, respectively [6]. However, when the sintering temperature is lower than 1500 °C, the lower driving force makes the grains not fully developed, resulting in low ceramic density and poor mechanical properties.

3. 3D Printing Technology

3D printing technology is a product of this digital age, and the application of this technology has brought new fields to the entire manufacturing industry. It has accurate and efficient molding efficiency, and it can also print shapes that are difficult to achieve in traditional manufacturing through layered accumulation [7]. 3D printing application areas are shown in Figure 1.

As shown in Figure 1, 3D printing has emerged in the fields of medical applications, architectural design, parts printing, toys and animation, daily necessities, and the automotive industry. Therefore, using 3D printing technology to process ceramic materials can not only solve the problem of the long processing cycle of ceramic products but also use its technical characteristics to produce special structural ceramics that cannot be obtained by traditional processing technology. It has broad market application prospects and practical value.

3.1. Process of 3D Printing Ceramics. The whole process of ceramic 3D printing is mainly divided into two stages. The first stage is the model preparation and slicing computer-aided design stage. The second stage is the process of 3D printer printing and ceramic firing. Figure 2 shows the flow of the 3D ceramic printing process.

As can be seen from Figure 2, after considering the characteristics of 3D printing technology, the appearance of the final work was determined, and 3DsMAX was used for 3D digital modeling to adjust and control the “triangular face value” of the 3D model. By printing with a 3D printer, it fixes parameter errors during the printing process and performs post-surface treatment and glazing on the printed works.

3.1.1. Preparation of the Printer before Modeling and Printing. Import the model file processed by slicing into the printer, and then start the preparation before the printer
prints; then load the vacuum mud, adjust the air pressure, and push the mud into the extruder. The gas pressure is related to the pipe length of the mud-conveying material. The longer the mud pipe, the stronger the thrust required to push the mud material, and the higher the pressure. The adjustment range is 0.3 kPa–0.7 kPa [8]. The pushing air pressure has a great influence on ceramic 3D printing. When the pressure is low and the thrust is insufficient, the extruded mud will obviously be broken, which will affect the printing. When the pressure is too high, the extruded mud flow will increase, which will affect the accuracy of ceramic modeling and printing and will cause certain damage to the interface parts of the printer. The air pressure used in all experiments in this paper was 0.5 kPa. In this paper, a flat plate covered with plastic film is used as the plane of the printing model to facilitate the movement of the printed body. The ceramic body will shrink during the drying process, so the printed body will generate shrinkage force at the bottom surface of the body in contact with the plane. As a base for printing, lightweight, absorbent paper is used to fill ceramic shapes.

3.1.2. Ceramic Modeling 3D Printing Molding Process. Before the ceramic model starts printing, the printer extrusion head is automatically homed. It runs the print operation from the origin, which will print a circle of mud on the outside of the first layer of the shape, checking whether the air pressure is stable and whether the distance between the extrusion head and the printing platform is appropriate by observing the smooth process of mud discharge [9, 10].

Figure 1: 3D printing application fields.

Figure 2: 3D printing ceramic process flow.
Then the process of printing and forming is officially started. The printing at the bottom is carried out in such a way that the shape surrounds the inner line and fills the line between each layer. The filling direction is 90 degrees. The lowering of the printing platform is controlled by the rotation of the screw, and the circles of lines are arranged to rise up, thereby stacking into a three-dimensional shape. The printing parameters that can be adjusted during the printing process are the printing speed and the size of the mud flow. The speed adjustment is mainly used for accurate printing and height modeling. When the printing reaches a certain height, the shaking of the blank is reduced by reducing the printing speed so as to avoid the tipping of the blank [11]. The control of the mud flow is to control the density of the overall shape. During the filling and printing process of the bottom and the increase in the mud flow at the junction between the bottom and the side wall, the bottom can be more compact and less prone to cracking and deformation. When printing with delicate patterns, the mud flow can be slightly reduced, making the line patterns more uniform and clear.

### 3.1.3. Trimming and Firing of the Printed Body
The shape of ceramic 3D printing is a clay body, which needs to be turned into a ceramic product through a firing process. Because the green body is formed by superimposing layers of mud strips, the surface will form layers of horizontal textures. In order to make a ceramic shape with a smooth surface, the surface of the green body is polished with tools such as sponge sand after printing. It forms a ceramic product with a smooth surface after glazing and firing. In terms of the use of glazes, most of the glazes sold on the market can be applied to the green body formed by ceramic 3D printing [12, 13]. In terms of the firing process of the 3D printing green body, the interlayer strength of the ceramic green body formed by 3D printing is relatively low, and it is easy to cause the phenomenon of cooling and cold cracking when combined with the firing of the glaze. This problem can be solved by slow cooling during the cooling process. When firing a ceramic model with a filling structure inside, it is necessary to pay attention to making ventilation holes on the molding bottom plate to discharge the internal gas and to reduce the heating rate during the firing process to avoid the phenomenon of frying.

### 3.2. 3D Printing Algorithm
Taking the blank at the front end of the current 3D printing path as a unit body and taking \( q_x \) and \( q_{x+1} \) as the heat flow for importing and exporting the unit body, respectively, \( S_c \) is the term of convection loss, and \( S_l \) is the term of heat conduction between the uncured slurry and the cured body after extrusion. Deduced according to the heat conduction process, the change in heat in the unit with time is shown as

\[
d\frac{\partial p}{\partial t} d_x = (q_x - q_{x+1}) l - S_c l d_x - S_l l d_x \tag{1}
\]

Here, \( d \) is the density, \( P \) is the specific enthalpy, \( t \) is the time, and \( k \) is the thermal conductivity; \( T \) is the average temperature of the unit body section, and \( x \) is the nozzle coordinate during the 3D printing process [14]. From this formula, the governing formula of the unit body can be obtained, as shown in formulas (2)–(4): 

\[
d\frac{\partial p}{\partial t} = k \frac{\partial^2 T}{\partial x^2} l d_x - S_c - S_l, \tag{2}
\]

\[
S_c = h \frac{T - T_{\infty}}{h}, \tag{3}
\]

\[
S_l = \frac{K}{w^2} (T - T_{\text{neigh}}). \tag{4}
\]

Here, \( h \) is the convective heat transfer coefficient, \( h_p \) is the height of the printing path, \( T \) is the temperature when the paste is extruded, \( T_{\infty} \) is the ambient temperature, \( w \) is the width of the unit body, and \( T_{\text{neigh}} \) is the temperature of the adjacent layer at the printing nozzle.

\[
-k \frac{\partial T}{\partial x} = h (T - T_{\infty}). \tag{5}
\]

In the formula, \( n \) is the normal vector of the nozzle position.

The model determines the temperature change in the green body with time at different positions along the stacking path during the 3D printing process, thereby judging the solidification of the green body [15]. The integral of the temperature difference between the slurry temperature and the freezing point over time is defined as the bonding potential so as to judge the bonding strength between the green layers:

\[
O = \int_0^q (T_M - T_C) \, dq, \tag{6}
\]

where \( O \) is the bonding potential, \( T_M \) is the temperature of the uncured slurry, \( T_C \) is the curing temperature value, \( t \) is the time, and \( q \) is the integral variable. The bonding potential takes into account both the effective bonding time (the time from extrusion to curing of the slurry) and the strength of molecular diffusion determined by the temperature difference. It is used to judge the bonding quality between layers in 3D printing. The larger the temperature difference, the stronger the bonding potential, and the stronger the bonding between the green bodies. The model has very important guiding significance for the preliminary determination of process parameters such as molding temperature [16]. In the experiment, the influence of temperature on the wettability between the layers of the green body was analyzed, and \( f_{\text{wetting}} \) was used to represent the degree of wetting between the adjacent layers of the green body. Its calculation formula is

\[
f_{\text{wetting}} = \frac{dO}{dT}. \tag{7}
\]

The contour offset is actually the parallel offset of the inner and outer contours of the model along different
directions. The key problem is how to realize the offset of the inner and outer contours to generate scan lines so that the 3D printer can rapidly manufacture [17, 18]. In actual production, this is very similar to tool interpolation in CNC machining. Tool interpolation is divided into two types: shortened and nonshortened.

In order to make this algorithm more universal, the temporary coordinate system xoy is taken, and the coordinate origin is at the intersection point Vi of the two line segments. Line segments $V_{i-1}V_i$ and $V_iV_{i+1}$ are any two adjacent line segments on the contour ring [19]. $\overrightarrow{L_i}$ and $\overrightarrow{L_{i+1}}$ are the vector forms of $V_{i-1}V_i$ and $V_iV_{i+1}$. $\overrightarrow{L_i}$ and $\overrightarrow{L_{i+1}}$ are the unit vectors of $\overrightarrow{L_i}$ and $\overrightarrow{L_{i+1}}$ in the coordinate system xoy, respectively.

\[
\begin{align*}
\overrightarrow{L_i} &= \alpha_i \hat{i} + \beta_i \hat{j}, \\
\overrightarrow{L_{i+1}} &= \alpha_{i+1} \hat{i} + \beta_{i+1} \hat{j},
\end{align*}
\]

(8)

where

\[
\begin{align*}
\alpha_i &= \frac{x_i - x_{i-1}}{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}, \\
\beta_i &= \frac{y_i - y_{i-1}}{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}, \\
\alpha_{i+1} &= \frac{x_{i+1} - x_i}{\sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}}, \\
\beta_{i+1} &= \frac{y_{i+1} - y_i}{\sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}}.
\end{align*}
\]

(9)

$V_{i-1}(x_{i-1}, y_{i-1})$, $V_i(x_i, y_i)$, and $V_{i+1}(x_{i+1}, y_{i+1})$ are the coordinates of $V_{i-1}V_i$ and $V_{i+1}$ in the original coordinate system XYO, respectively [20]. According to the definition of the direction of the contour ring, the straight line formula after the line segments $\overrightarrow{L_i}$ and $\overrightarrow{L_{i+1}}$ are offset by a D value can be obtained as

\[
\begin{align*}
-b_i x + a_i y &= -D, \\
-b_{i+1} x + a_{i+1} y &= -D.
\end{align*}
\]

(10)

Because the straight lines $\overrightarrow{L_i}$ and $\overrightarrow{L_{i+1}}$ are not parallel (otherwise, $\overrightarrow{L_i}$ and $\overrightarrow{L_{i+1}}$ are on the same straight line), solving formula (10) with $a_i \beta_{i+1} - a_{i+1} \beta_i \neq 0$ can obtain the coordinate value of the new intersection in the coordinate system xoy after the two line segments are offset:

\[
\begin{align*}
x &= \frac{(a_{i+1} - a_i)D}{\alpha_i \beta_{i+1} - a_{i+1} \beta_i}, \\
y &= \frac{(\beta_{i+1} - \beta_i)D}{\alpha_i \beta_{i+1} - a_{i+1} \beta_i}.
\end{align*}
\]

(11)

Transforming it to the original coordinate system XYO can get the coordinate value of the new intersection:

\[
\begin{align*}
X &= x_i + x, \\
Y &= y_i + y.
\end{align*}
\]

(12)

In this way, by calculating the new intersection points of each adjacent line segment in the contour ring after offset one by one, the shape and position of the offset contour ring can be determined, and the contour offset filling line can be formed. The new intersection coordinates of the line and the arc are

\[
\begin{align*}
x &= a_i(x_0 + \beta_j y_0) - r\beta_j + s\alpha_i \sqrt{(R + r)^2 - (a_i y_0 - \beta_j x_0 - r)^2}, \\
y &= \beta_j (a_i x_0 + \beta_j y_0) + r\alpha_i + s\beta_j \sqrt{(R + r)^2 - (a_i y_0 - \beta_j x_0 - r)^2},
\end{align*}
\]

(13)

where $r$ is the tool radius, $(x_0, y_0)$ is the center coordinate of the arc, and $R$ is the arc radius. Here, $s = -\text{sgn}(a_i x_0 + \beta_j y_0)$, and the intersection point can be obtained by substituting S into formula (13).

The photocuring performance of ceramic paste refers to the curing ability after being exposed to light [21]. For pure photosensitive resin, its photocuring performance includes two indicators: curing depth and curing reaction critical energy (light intensity); the relationship between the two is shown in formula (14):

The photosensitive resin curing thickness formula is

\[
C_{d} = D_{p}\ln \frac{E}{E_{c}}.
\]

(14)

Here, $C_{d}$ is the curing depth, $E$ is the incident light intensity of the light projected by the projector, $E_{c}$ is the critical light intensity when the resin undergoes a curing reaction, and $D_{p}$ is the projection depth coefficient, a decimal which is a characteristic of the photosensitive resin itself [22]. When the photosensitive resin is cured by specific light irradiation, the oligomer in the photosensitive resin absorbs the energy of photons and undergoes a photocuring chemical reaction. The photocuring process follows the basic law of photochemical reaction, as shown in the formula:

\[
I = I_0 e^{-kd}.
\]

(15)

Formula (15) shows that the light intensity decreases exponentially with the transmission depth. For the ceramic slurry, when the light irradiates the ceramic powder, reflection and refraction will occur. It also needs to take into account the effect of ceramic particles on light, so the formula is corrected for light, and the scattering formula of the ceramic slurry can be obtained as shown in the following formula:

\[
D_{p} = \frac{2d_{50}}{3Q} \times \frac{n_{p}^2}{\Delta n}.
\]

(16)

Here, $d_{50}$ is the average particle size of the ceramic powder; $\Delta n$ is the difference between the refractive index $n_{p}$ of the ceramic powder and the refractive index $n_{0}$ of the
photosensitive resin, a decimal; $\bar{Q}$ is the scattering coefficient, a decimal, depending on the solid content of the slurry and the wavelength of the light.

4. Design and Construction of Experimental Platform for 3D Printing Ceramic Technology

4.1. 3D Printing Processing Technology

4.1.1. Principle of 3D Printing. Surface molding 3D printing is to project the sliced image of the model to be printed on the surface of the photosensitive resin in the form of a mask through optical equipment such as a projector. The photosensitive resin in the image is cured by irradiation, thereby achieving selective molding of the cured layer. The object slice images are projected, cured, and finally stacked into printed parts.

4.1.2. Classification of 3D Printing Processing Technology. According to the positional relationship between the light source and the printing surface, the surface molding 3D printing process can be divided into the upper projection ceremony surface molding process and the lower projection ceremony surface molding process. The structure of the upper projection ceremony surface molding equipment is shown in Figure 3.

As shown in Figure 3, the working cycle of the upper projection ceremony surface forming process is generally divided into four processes:

1. Use the modeling software to draw the model of the part to be printed.
2. Using slicing software, slice the model to obtain the slice pattern of the model.
3. When the projector is working, the mask pattern of the printed part is projected onto the surface of the photosensitive resin. At this time, the resin of the printing base is cured, formed, and adhered to the printing base.
4. The Z-axis slide moves down and moves a distance of a layer thickness. After the resin liquid level is leveled, the projector is turned on again, and the resin between the cured layer and the liquid surface is cured under the projection of the next layer of the sliced image.

Since the projector is placed on the top, the resin liquid level is not restricted, so this technology is also called the free liquid surface process.

4.1.3. Forming Process of the Lower Projection Ceremony Surface. The bottom-mounted projection ceremony surface-forming equipment is similar to the top-mounted structure, except that the projector is located the processing plane, as shown in Figure 4.

It can be seen from Figure 4 that in the forming process of the lower projection ceremony surface, the projection light is irradiated from the resin disc. The photosensitive resin cured by light has only a part of the resin bound under the printing base, and the height of the cured resin is equal to the thickness of the printed layer. This technique is also called the constrained surface process. After printing a layer, the Z-axis slide moves up instead of moving down. Since the resin under the printing base is cured by light and adheres to the base, after printing a layer, the slide table moves up, allowing the resin to flow into the gap, and then a printing cycle can be completed.

4.1.4. Comparison of Two Surface-Forming Processes. In the top-mounted projection ceremony process, the sliding table is lowered by a distance of one layer thickness to ensure that the distance between the cured layer and the resin liquid surface is still one layer thickness at this time. In the underprojection ceremony process, the processed parts are adhered to the bottom of the printing base. Therefore, after the printing base moves upward for a certain distance, the descending distance should be one layer thickness less than the ascending distance to ensure that the distance between the processed layer and the bottom of the resin disc is one layer thickness.

4.2. Improvement of Surface-Forming Process Suitable for Ceramic Slurry. According to the comparison in the previous section, considering the particularity of the ceramic slurry, it is difficult to guarantee the accuracy of the cured layer if the overhead projection ceremony technique is used. In addition, the viscosity of the ceramic slurry is high, resulting in poor surface-processing quality and unsatisfactory printing effect. It adopts the lower projection ceremony surface forming process, and its structure needs to be improved to meet the printing requirements of high-viscosity paste.

4.2.1. Improvement of Bottom Glass of Resin Tank. When a layer of printing is completed, the printing base moves upward. Since the cured layer is tightly adhered to the glass at the bottom of the resin tank, it is difficult to separate the cured layer from the glass when lifting. In severe cases, it can also cause the resin tank to tilt, destroying the structure of the printer. Therefore, laying the Teflon film on the bottom glass of the resin tank can effectively reduce the separation resistance of the cured layer and the resin tank because of its low friction coefficient, good wear resistance, and no reaction with the resin, thereby protecting the bottom glass.

4.2.2. Improvement of the Separation Process between the Cured Part and the Resin Tank during Printing. In traditional printing equipment, after the resin is cured by light, the Z-axis slide is lifted. At this time, the cured layer is double-bonded by the upper printing base and the bottom surface of the resin tank, and it is difficult to ensure that each layer is firmly adhered, considering the separation of the printed part from the resin tank. The longitudinal adhesive separation force is much greater than the tangential adhesive
separation force. The improved resin disk structure is shown in Figure 5.

As can be seen from Figure 5, the resin tank was changed into a disc shape, and semicircular PDMS (polydimethylsiloxane) was laid on one side. When the resin is cured, the resin disk is first rotated by 180° and then the Z-axis is moved upward. Due to the existence of the height difference, the cured layer will not be bonded by the glass. At this time, lifting the Z-axis slide table can ensure that the printed part is firmly adhered to the printing base. At the same time, during the spinning process, the resistance is greatly reduced due to the existence of the Teflon film, and the PDMS can also protect the plexiglass from impact.

4.3. Construction of Prototype 3D Printing of Ceramic Materials. The improved 3D printer model of ceramic material is divided into three parts: a hardware system, control system, and software system. The hardware system includes a resin disk-rotating device, Z-axis-lifting device, scraper-coating device, and projection device. The control system includes the control system of the lower computer of the printer. The software system includes printer control software and model slice software.

5. Rheological Properties and Dispersion of Silicon Carbide Ceramic Slurry

5.1. Effect of Carbon Black Content on Slurry Rheological Properties and Dispersion. In reactive sintering, carbon black acts as a carbon source to provide liquid silicon reaction sites that can fill voids in the green body. The amount of carbon black added will affect the structure and properties of the reaction sintered silicon carbide. Therefore, it is meaningful
to study the effect of the amount of carbon black added on the paste direct-writing printing. The shear rates of the slurries with different carbon black contents are shown in Figure 6.

Figure 6 shows the shear rate–shear viscosity curves and shear rate–shear stress curves of slurries with different carbon black contents at shear rates of 0.01–1000 s when the chopped carbon fiber content is 20 vol%. It is not difficult to find that the slurry exhibits similar viscosity behavior under different carbon black contents; the viscosity decreases with the increase in the shear rate, and the shear stress gradually increases with the increase in the shear rate. It shows that the prepared slurries are all shear-thinning slurries. The reason for this phenomenon is that under the high shear rate of the slurry, the internal particles are driven by the shear force to move rapidly. The slurry is uniformly dispersed and has no large agglomeration, so the movement of the particles will not be hindered by each other. The figure shows that the difference in viscosity of the slurry with different carbon black contents is not obvious. When the shear rate is less than 10 s, the slurries with different carbon black contents maintain stable shear stress. When the shear rate is more than 10 s, the shear stress increases sharply, and the slurry with a carbon black content of 20 vol % exhibits the lowest shear rate. The reason for this phenomenon may be that the binder is not completely wrapped on the surface of the ceramic powder and carbon black, but the introduction of carbon black has a certain lubricating effect. The viscoelasticity of the slurry with different carbon black contents was further studied; the amplitude sweep test was carried out at a frequency of 1 Hz, and the curve of shear stress modulus and its corresponding shear stress were obtained as shown in Figure 7.

From Figure 7, it can be found that under low shear stress, the slurries with different carbon black contents all exhibit a distinct linear viscoelastic region. With the increase in shear stress, the slurry appeared shear-thinning. The slurry with a carbon black content of 20 vol % first reached the flow point under a shear stress of 25 Pa, and the slurry was transformed from a colloid to a fluid state. The slurry with 15 vol % carbon black content has the highest initial modulus, and the slurry with 10 vol % and 15 vol % carbon black content shows similar flow points, where the shear stress is about 44 Pa. This means that the slurry with high carbon black content requires less extrusion pressure during the direct writing process, making it easier to achieve extrusion of the slurry. The uniform dispersion of the silicon carbide ceramic composite slurry can reduce the extrusion pressure during the direct writing process of the slurry. The microscopic morphologies of the slurries with different carbon black contents after drying are shown in Figure 8. It can be seen from Figure 8 that the silicon carbide powder has a weak agglomeration and the chopped carbon fibers are distributed evenly, which avoids the needle clogging caused by the agglomeration of the chopped carbon fibers during extrusion.

5.2. Preparation Technology of Ceramic Slurry. First, the vertical printing base is raised, and the ceramic slurry to be tested is poured into the resin tray; the printer resin tray is
Figure 7: Shear stress of slurries with different carbon black contents. (a) Modulus curve and (b) loss factor curve.

Figure 8: Dispersion morphologies of dry slurries with different carbon black contents. (a) 0 vol %; (b) 10 vol %; (c) 15 vol %; (d) 20 vol %.
turned on, which uses a scraper to smooth the slurry; the projector is turned on, a 10 x 10 mm square pattern is projected, the exposure time is set to 10 s, and then a screw micrometer is used to measure the cured layer thickness of each paste. The statistics are shown in Table 1.

It can be seen from Table 1 that for alumina ceramic slurry, when the solid phase content is the same, the smaller the powder particle size, the smaller the solidification depth. When the particle size of the powder is the same, the lower the solid content, the greater the solidification depth. According to the curing depth of the ceramic paste, it can guide the selection of the printing layer thickness when printing ceramic parts. It can increase the printing speed by appropriately increasing the printing layer thickness. When the layer thickness cannot exceed the maximum curing depth of the paste, appropriately reducing the printing layer thickness can improve the printing quality, but the printing is slower. In addition, the layer thickness is set too low, and the precision of the lead screw of the vertical slide table is difficult to guarantee.

Since the photosensitive resin is a mixture, the specific decomposition temperature cannot be determined, so different degreasing temperature sections are set for degreasing experiments. The square ceramic green body obtained in the step is the experimental object. The parameters of the part degreasing and sintering stage are shown in Table 2.

As can be seen from Table 2, starting from room temperature, the temperature is heated to 300°C at a rate of 1°C/min and incubated for 120 min. The temperature was raised to 500°C at a rate of 1°C/min and maintained for 120 min. The temperature was raised to 800°C at a rate of 19°C/min and maintained for 120 min. The temperature was raised to 1000°C at a rate of 1°C/min, and the temperature was maintained for 120 min. During the cooling stage, the temperature was cooled to room temperature at 2°C/min, and the size and quality of the ceramic parts after sintering at different degreasing temperatures were measured. The ceramic parts obtained by degreasing and high temperature sintering were measured. Various parameters need to be measured and calculated to judge the printing and sintering effect. The firing shrinkage of ceramic parts in three directions at different sintering temperatures is calculated as shown in Table 3.

It can be seen from Table 3 that with the increase in sintering temperature, the firing shrinkage of ceramic parts increases gradually. The reason is that the sintering driving force required for sintering ceramic parts is the surface-free energy of alumina particles. The higher the sintering temperature, the higher the sintering degree, and the greater the firing shrinkage of the ceramic. At a sintering temperature of 1600°C, the alumina square sample with a solid content of 60% has a shrinkage rate of 15% to 16% in three directions. In addition, there is little difference in each direction, and it can be considered that the interior of the part is completely sintered and isotropic. In the high temperature sintering stage, 1600°C is the holding temperature, the heating rate is 0.5°C/min, and the holding time is 600 min. The sintering effect of ceramic parts is better. The measured shrinkage rate of the ceramic sample does not exceed 16%, the porosity is not high, and the density is 53.2%. The results show that the ceramic parts prepared by this process can meet the basic performance requirements.

### Table 1: The curing depth of ceramic slurry with different solid contents.

<table>
<thead>
<tr>
<th>Solid phase content (%)</th>
<th>Particle size (μm)</th>
<th>Curing depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>5</td>
<td>0.811</td>
</tr>
<tr>
<td>50</td>
<td>1</td>
<td>0.772</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>0.546</td>
</tr>
<tr>
<td>50</td>
<td>10</td>
<td>0.293</td>
</tr>
<tr>
<td>60</td>
<td>5</td>
<td>0.764</td>
</tr>
<tr>
<td>60</td>
<td>1</td>
<td>0.603</td>
</tr>
<tr>
<td>60</td>
<td>50</td>
<td>0.376</td>
</tr>
</tbody>
</table>

### Table 2: Parameters of part degreasing and sintering stage.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Length (L/mm)</th>
<th>Width (W/mm)</th>
<th>Width (W/mm)</th>
<th>Width (W/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>25.17</td>
<td>25.03</td>
<td>5.05</td>
<td>2.63</td>
</tr>
<tr>
<td>300</td>
<td>25.15</td>
<td>25.00</td>
<td>5.02</td>
<td>2.61</td>
</tr>
<tr>
<td>500</td>
<td>25.08</td>
<td>24.98</td>
<td>4.82</td>
<td>2.41</td>
</tr>
<tr>
<td>1000</td>
<td>24.97</td>
<td>24.91</td>
<td>4.76</td>
<td>1.51</td>
</tr>
</tbody>
</table>

### Table 3: Sintering shrinkage of ceramic parts at different sintering temperatures.

<table>
<thead>
<tr>
<th>Sintering temperature (C)</th>
<th>Firing shrinkage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
</tr>
<tr>
<td>1400</td>
<td>7.9</td>
</tr>
<tr>
<td>1500</td>
<td>12.6</td>
</tr>
<tr>
<td>1600</td>
<td>15.8</td>
</tr>
</tbody>
</table>

47%, the bulk density is 2.27 g/cm³, and the density is 53.2%. The results show that the ceramic parts prepared by this process can meet the basic performance requirements.

5.3. Influence of Chopped Carbon Fiber Content on the Rheological Properties and Dispersion of the Slurry. Figure 9 shows the shear rate–viscosity curve and shear rate–shear stress curve of the silicon carbide ceramic slurry with different contents of chopped carbon fibers at a shear rate of 0.01–1000 s⁻¹.

It can be seen from Figure 9 that within the test range, after adding chopped carbon fibers with different contents, the silicon carbide ceramic slurry showed a state of shear thinning. As the shear rate increases, the shear stress of the slurry first increases and then decreases. The viscosity of the slurry decreased gradually with the increase in the amount of chopped carbon fiber added; the viscosity with 20 vol % chopped carbon fiber content was the smallest, and the decrease in the viscosity increased. This is due to the gradual decrease in the binder on the individual chopped carbon fibers in the package as the content of chopped carbon fibers increases. The chopped carbon fibers provide more voids for the ceramic particles in the slurry, resulting in a reduced spacing between particles. The intermolecular attraction is weakened, which makes the slurry more prone to slipping of chopped carbon fibers under the action of shearing force. Therefore, the viscosity reduction in the pulp with high
Figure 9: Shear rate under different Cr contents. (a) Viscosity curve and (b) shear stress curve.

Figure 10: Shear stress under different Cr contents. (a) Modulus curve and (b) loss factor curve.
chopped carbon fiber content is larger. Figure 10 shows the shear stress–modulus curves and shear stress–loss factor curves of SiC ceramic slurries with different chopped carbon fiber contents after scanning at a frequency of 1 Hz.

Figure 10 shows the viscoelastic region’s gel–fluid transition characteristics of shear-thinning fluids. Without the addition of chopped carbon fibers, the pulp exhibited the highest storage and dissipation modulus. With the increase in chopped carbon fiber content, the yield stress value of the pulp decreases, and the tanδ value also tends to increase under the same shear stress. This indicates that pulp with high chopped carbon fiber content has a lower modulus and is more prone to gel–fluid transition. Because the chopped carbon fiber has a high aspect ratio, the binder is difficult to wrap around the surface of the fiber, and the bonding effect is weak. The weakening of the coating effect of the binder on the surface of the chopped carbon fibers and the “bridging” effect of the short fibers themselves in the slurry make the chopped carbon fibers more prone to random shear slip under high shear stress.

6. Conclusion

Using 3D printing technology to process ceramic materials has advantages that are difficult to compare with traditional ceramic processing methods. It has fast processing speed and high forming precision and can realize manufacturing complex structural ceramic parts and the mass production of nonstandard parts. It has great practical value in the current application of ceramic materials. This paper focuses on the research on the processing technology of ceramic materials based on surface forming 3D printing technology. It mainly includes the research on the surface molding 3D printing process, the research on the preparation process of ceramic slurry suitable for surface molding 3D printing technology, and the research on the ceramic green body printing and sintering process. At present, the sintering degree is judged by the quality, size, and surface state of the sintered sample, and the sintering state can be accurately judged by observing the internal microscopic electron microscope image of the sample; in addition, the sintering process curve can be further optimized.

Data Availability

No data were used to support this study.

Conflicts of Interest

There are no potential competing interests in our paper. All authors have reviewed the article and have approved submission to your journal.

References


