Research Article

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Handcrafted digital light processing apparatus for additively manufacturing oral-prosthesis targeted nano-ceramic resin composites

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Abstract: 3D-printing finds increasing applications including the dental implant. We report in this study a nicely printed and then cured composite consisting of nano-ceramic and photosensitive resin, targeting oral prosthesis application. The results show that the 3D-printed material has good geometry accuracy and satisfactory hardness, justifying its potential as an advanced manufacturing methodology for future dentistry.

Keywords: 3D printing & additive manufacturing, light-curing, nano-ceramic resin, digital light processing

1 Introduction

3D-printing technology, also known as additive manufacturing, is a rapid prototyping technology [1–3]. It is the latest achievement made from a combination of processing technology, computer-aided design and manufacturing (CAD/CAM), and material science. Since the introduction of 3D-printing technology in the 1980s [4], it has been developed rapidly due to its high precision, near-net shaping capability, and capability to realize customization of qualified parts [5].

Manufacturing in the dental field is often highly personalized. In traditional dental manufacturing, resin materials used for dental restorations are often piled by hand. There are material wastes in this manufacturing process. 3D-printing technology can overcome the shortcomings in terms of material waste; it is also capable to provide personalized medical devices [6,7]. Currently, 3D-printing technologies used in dental manufacturing include selective laser sintering, selective laser melting, stereolithography, and digital light processing (DLP). The DLP technology is based on the digital micromirror device and light polymerization. The basic principle of the DLP is as follows: Applying a light beam of a specific wavelength to the resin surface, then the resin material is cured after absorbing the beam energy [8]. It has been used to prototype the bridge and provide a model for dental restoration [9,10]. Chen et al. [11] effectively improved the mechanical properties and antibacterial properties of PMMA composite resin by adding 1% TiO2, and they have proved that PMMA (TiO2-1%-PEEK-1%) is a dental restoration photocurable resin suitable for the DLP processing. DLP can also be used for printing invisible orthodontic models to create braces suitable for orthodontics [11].

Digital dentistry application requires special materials [12]. Biocompatibility is a key consideration. The previous light-cured 3D-printed materials, however, normally do not meet the hardness required for clinical crowns. Crowns for clinical application are still mostly made by the CAD/CAM milling technology.

Acrylic block copolymers have good physical properties and can be used as temporary restoration materials for dental 3D printers [13]. Ceramic materials usually have high mechanical strength, hardness, good thermal stability, and chemical stability [14]. Meanwhile, resin materials tend to have good flowability and formability. Nano-porcelain resin composites are made of nano-ceramic particles embedded in a highly cured resin matrix [15]. It combines the characteristics of nano-porcelain and resin and has the characteristics of high hardness and low brittleness. From a clinical perspective, nano-ceramic resin composites appear to be the most reliable materials to establish internal repairs, restore structural integrity, and
endodontic treatment [16]. Researchers report that dental clinical light-cured nano-ceramic resins are ideal crown materials in terms of physicochemical properties and esthetic properties [17–20]. However, hand-piled resin materials require a lot of practice time for junior technicians. Therefore, the nano-ceramic resin inlays have not been widely promoted for clinical practice.

The DLP technology can manufacture inlays quickly and accurately. Due to the high concentration of nano-ceramic resin, however, there is almost no matching DLP device yet. Therefore, we reconstructed a DLP equipment in this study to print nano-ceramic resins. Direct 3D printing of the nano-ceramic resin composites has been achieved. The differences between 3D-printed dental prostheses and traditional hand-piled ones were compared.

2 Materials and methods

2.1 Construction of the handcrafted DLP

The schematic diagram of the handcrafted 3D printer is shown in Figure 1. The handcrafted DLP printing equipment is equipped with a special coating device, which consists of a rotating system and a scraper, to deal with the high viscosity of the nano-ceramic material effectively. The coating apparatus provides a flat slurry layer for the resin material, and the DLP system selectively exposes the slurry to light at a wavelength of 405 nm to initiate free radical photopolymerization. The DLP system can change in layer thickness, ranging from 15 to 75 μm. The Z-axis of the equipment is driven by a motor. The size of the building platform is 51.2 mm × 32 mm.

Table 1: 3D-printing parameters used in the present study

<table>
<thead>
<tr>
<th>Ratio (NC:NF)</th>
<th>Base time (ms)</th>
<th>Exposure time (ms)</th>
<th>Brightness (cd)</th>
<th>Layer thickness (μm)</th>
<th>Support time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1</td>
<td>10,000</td>
<td>7,000</td>
<td>100</td>
<td>50</td>
<td>8,000</td>
</tr>
<tr>
<td>1.1:1</td>
<td>10,000</td>
<td>7,500</td>
<td>100</td>
<td>50</td>
<td>8,000</td>
</tr>
<tr>
<td>1.2:1</td>
<td>10,000</td>
<td>8,000</td>
<td>100</td>
<td>50</td>
<td>8,000</td>
</tr>
<tr>
<td>1.3:1</td>
<td>10,000</td>
<td>8,500</td>
<td>100</td>
<td>50</td>
<td>8,000</td>
</tr>
<tr>
<td>1.426:1</td>
<td>11,000</td>
<td>9,000</td>
<td>100</td>
<td>50</td>
<td>8,000</td>
</tr>
</tbody>
</table>

To meet the machine’s printing matching parameters, the printer background parameters were set as presented in Table 1.

2.2 Sample preparation

The Tetric N-Ceram (NC) and Tetric N-Flow (NF) nano-ceramic resin composites from Ivoclar Vivadent were selected as experimental materials (details as shown in Table 2). The NC nano-ceramic resin composite has good physical properties but lower flowability. To obtain good flowability, the NC nano-ceramic resin composite was mixed with the NF resin composite (a kind of flowable resin). In our preliminary experiment, it showed that when the mass ratio of NC:NF reached 1.426:1, the composites could reach the highest concentration that is possible to be printed by the handcrafted 3D-printing device. When the mass ratio is higher than 1.426:1, the internal viscosity of the composite is too large. The materials will generate internal friction during printing and difficult to be manufactured by DLP. The mixture will directly

![Figure 1: Diagram of the handcrafted 3D printer and the main machine parameters.](image-url)
adhere to the scraper and cannot be scraped flat by the scraper unit in the handcrafted equipment. Therefore, in this experiment, we designed the mixing mass ratios as 1:1, 1.1:1, 1.2:1, 1.3:1, and 1.426:1 to study the influences of the manufacturing method and the filler ratio on the physical properties of the restorations. Before printing or manually hand-piling test, the resin composites were mixed according to the aforementioned different mass ratios. For instance, 7 g NC and 7 g NF resin were put into the beaker and then stirred thoroughly for 10 minutes to obtain a 1:1 well-mixed resin material. In the same mixing way, 7 g NC resin and 6.36 g NF, 7 g NC resin and

<table>
<thead>
<tr>
<th>Table 2: List of used materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tetric N-Ceram (NC)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Tetric N-Flow (NF)</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Figure 2: Comparison between 3D printing and hand piling for making oral prosthesis targeted nano-ceramic resin composites. (a) 3D printing and (b) hand pile.
5.83 g NF, 7 g NC resin and 5.38 g NF, or 7 g NC resin and 4.91 g NF resin were mixed well, reaching the mass ratios of 1.1:1, 1.2:1, 1.3:1, and 1.426:1, respectively. Table 1 further lists the ingredients and recommended light-curing conditions for the two raw materials.

Figure 2 shows the processes of sample preparation by DLP, which is compared with that of hand piling. The testing samples in Group A were printed by the handcrafted DLP equipment. The Group B samples were hand piled. All the nano-ceramic resin samples were designed into the dimensions of $4 \times 4 \times 5$ mm$^3$ ($X$: 4 mm, $Y$: 4 mm, and $Z$: 5 mm) in this study.

According to the mixer ratios, the samples in Group A were further divided into five subgroups: Group A-1, Group A-1.1, Group A-1.2, Group A-1.3, and Group A-1.426. Ten testing samples were prepared for each subgroup. Ten testing samples were arranged for each subgroup too.

The light-curing nano-ceramic resin was laminated and light-cured by the LED light-curing lamp (wavelength = 405 nm, light-curing time = 20 s; National High-tech Zone, Guilin, China). The light source intensity of the lamp varied from 1,000 to 1,200 mW/cm$^2$.

After printing, all the samples in Group A and Group B were cured in a handcrafted supplementary curing oven for 10 min.

### 2.2.1 Handcrafted supplementary curing oven

Curing ovens on the market are mainly used for processing established resins. Those curing furnaces cannot meet the power required for curing the nano-ceramic resin composites in the present study. Therefore, according to the light-curing requirements of different nano-ceramic resin composites, a supplementary curing furnace containing multiple power selection was also made, which was designed to contain three types of lights with different wavelengths of 365, 385, and 405 nm, respectively. The light source intensity of the lamp is from 2 to 9 W/cm$^2$. By turning on the lights separately, simultaneously, or by controlling the light-curing duration, the handcrafted curing oven can meet the curing requirements of different resin composites including the current one.

### 2.3 Methods

#### 2.3.1 Viscosity test

To accurately measure the viscosity of nano-ceramic resin materials doped with the resin materials, the composite viscosity with different resin material ratios was measured using a Brinell viscometer (NDJ-1, Cangzhou Zhulong Engineering Instrument Co., Ltd.).

#### 2.3.2 Hardness test

Hardness was measured by an HXD-1000TMC Vickers microhardness tester (Shanghai Taiming Optical Instrument Co., Ltd.). The samples were polished following the standard procedures, then blown dried, and checked for sample surface under the microscope. The microhardness test was performed under a 9.8 N indentation load for 10 s. Each test point has a circumferential separation radius of 200 μm.

#### 2.3.3 Tensile test

A universal tester (Instron 5965; Norwood, Massachusetts, USA) was used to determine the tensile strength of 100 samples at a crosshead speed of 1 mm/min. Each sample is placed vertically or horizontally in a specially designed fixture and then placed on the base of the testing machine. A stainless steel rod (diameter 6 mm; length 122 mm) with a blunt surface is placed on top of the sample, and a compressive load is applied until it fails.

#### 2.3.4 SEM observation

After the hardness test, the tested samples’ surfaces from group A and group B were observed by a scanning electron microscope (SEM; VEGA 3 BSH, SHENZHEN, China). Before the SEM observation, the samples were coated with gold.

#### 2.3.5 X-ray diffraction measurements

X-ray diffraction (XRD) measurements were performed using the Empyrean X-ray diffractometer (PANalytical, Holland) with filtered Cu Kα radiation ($\lambda = 1.5406$ Å, operating at 45 kV and 40 mA).

#### 2.3.6 Density test

The density of the sample was measured by using an Archimedes-principle density tester (MH-300T). By comparing the quality difference of fixed volume test block in water and air, the density of the test block was further obtained. By calculating the average density of 77 test blocks, the ratio of the average density to the
theoretical density of the material is taken as the material density.

2.3.7 Error rate measurement

The sample size in this study is $4 \times 4 \times 5 \text{mm}^3$. A VSM300 precision measuring instrument (Shanghai Taiming Optical Instrument Co., Ltd.) was used to test the dimensional error of samples from Group A under different NC:NF ratios.

Absolute error is equal to half the confidence interval. When the confidence interval and the length of the confidence interval are known, the absolute error plays an important role. The difference between the exact value $T$ and its measured value $X$ is referred to as the absolute error. It is recorded as $E_{a1} = X_{\text{Measurements}} - T_{xy}$, $E_{a2} = Z_{\text{Measurements}} - T_z$. $E_{xy}$ and $E_z$ are the relative errors in the $x$-$y$ and $z$ direction. The ratio of the absolute error is obtained by the measurement to the true value measured, multiplied by 100%, and expressed as a percentage.

According to the relative error formulas, the magnitude of the deformations was determined as follows:

$$E_{xy} = (E_{a1}/T) \times 100\%,$$

$$E_z = (E_{a2}/T) \times 100\%,$$

Note: $E_{a1} = X_{\text{average value}} - T_{xy}$, $E_{a2} = Z_{\text{average value}} - T_z$.

2.3.8 Compositional analysis

To further accurately measure the composition of the 3D-printed sample, the 3D-printed resin compositional was measured using XRD (PANalytical Empyrean, the Netherlands).

2.3.9 Statistical analysis

The micro-hardness data of each specimen were analyzed statistically by the $t$-test. Ten results were used for each subgroup. The preparation method and ratio were used as two factors to analyze the hardness of testing samples by two-way ANOVA. Statistical significance in all analyses was set at a 5% probability level. The statistical analysis was performed using the Statistical Product and Service Solutions software (SPSS 13.0 for Windows).

3 Results

3.1 Viscosity test results

The viscosities of nano-ceramic resins with different ratios are shown in Figure 3. They were tested as $7,298 \pm 167$, $8,091 \pm 241$, $8,467 \pm 241$, and $8,974 \pm 311 \text{ mPa s}$, respectively. Such high levels of viscosity justify the use of the currently developed DLP facility.

3.2 Phase analysis of the 3D-printed NC

XRD was used to study the phase constitution of the 3D-printed NC (Figure 4). It can be seen from this figure that the oxide phases dominate, matching the raw materials presented in Table 2.

3.3 Hardness test and geometry error test results

Regarding the DLP processing, the required light time for different composites was 7,000, 7,500, 8,000, 8,500, and 9,000 ms, respectively. Through our preliminary experiment, it is confirmed that the supplementary curing was able to cure the NC or NF nano-ceramic resin composites by using the handcrafted curing oven. When the power was adjusted to 60 W/cm², the curing furnace could reach the optimal power and the curing time could be set as 10 min.

The hardness test results are presented in Table 3 and Figure 5. As for hand-piled resin samples, Group B-1.1, Group B-1.2, Group B-1.3, and Group B-1.426 obtained hardness that meets the clinical hardness standard of 311.8 MPa [21]. Group B-1.1 had the minimum hardness.
of all subgroups, which still reaches the clinical requirement of 322.6167 MPa. It was 10.8167 MPa higher than the clinical hardness standard.

In the 3D-printed groups, Group A-1.2, Group A-1.3, and Group A-1.426 obtained hardness that meets the clinical standard as of 311.8 MPa. As for the mass ratio of 1.2:1 in Group A, the hardness is 34.125 MPa higher than the clinical hardness standard and can meet the clinical requirement of 345.925 MPa. In comparison, under the same mass ratio, the hardness of group A is lower than that of group B. However, there was no statistical difference between two subgroups under the same mass ratios (i.e., NC:NF = 1:1, 1.1:1, 1.2:1, 1.3:1, or 1.426:1).

The hardness reverse side test results are presented in Table 4 and Figure 6. The hardness test results of the reverse side showed that in the 3D-printing group, when the NC:NF mass ratio of the nano-ceramic resin composite material is 1.2:1, 1.3:1, and 1.426:1, the hardness of 3D-printed nano-ceramic restorations (test samples) could meet the requirements of oral restoration. When the NC:NF mass ratio of the nano-ceramic resin composite material is 1.3:1 and 1.426:1, the hardness of nano-ceramic restorations (test samples) of the manual group could also meet the requirements of oral restorations.

Among the subgroups in Group A or Group B, when the ratio of nano-ceramic resin (NC:NF) increased, the hardness of samples also increased. Within Group A, the hardness of Group A-1 was significantly lower than that of Group A-1.2, Group A-1.3, or Group A-1.426. Group A-1.426 had hardness significantly higher than all other subgroups. As shown in Figure 5, the hardness of Group A-1.3 and that of Group A-1.426 were higher than the clinical requirements and could be used in dental restorations.

The relative geometry error results of the Group A samples are presented in Table 5, and the absolute error results are presented in Table 6. The relative error and the absolute error were used to represent the error rate of sample deformation in this study. The error curves are shown in Figure 7.

The results of accuracy error show that the 3D-printed samples, made by the handcrafted DLP, meets the precision requirement for clinical oral cavity restoration, whose accuracy tolerance is ≤0.2 mm.

As shown in Figure 7, the green line represents the maximum absolute error (the accuracy is 0.20 mm) that

![Figure 4: XRD pattern of the DLP processed resin.](image4)

![Figure 5: Hardness comparison between hand-made and 3D printed, with a reference to the clinical requirement.](image5)

### Table 3: Hardness test results

<table>
<thead>
<tr>
<th>Ratio (NC:NF)</th>
<th>1:1</th>
<th>1.1:1</th>
<th>1.2:1</th>
<th>1.3:1</th>
<th>1.426:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand piled</td>
<td>280.58&lt;sup&gt;a&lt;/sup&gt;</td>
<td>322.62&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>379.04&lt;sup&gt;b&lt;/sup&gt;</td>
<td>459.76&lt;sup&gt;b,c&lt;/sup&gt;</td>
<td>497.93&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>±SD</td>
<td>19.29</td>
<td>18.34</td>
<td>18.68</td>
<td>19.78</td>
<td>21.98</td>
</tr>
<tr>
<td>3D printed</td>
<td>247.51&lt;sup&gt;a&lt;/sup&gt;</td>
<td>290.64&lt;sup&gt;a&lt;/sup&gt;</td>
<td>345.93&lt;sup&gt;b&lt;/sup&gt;</td>
<td>421.41&lt;sup&gt;c&lt;/sup&gt;</td>
<td>471.23&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>±SD</td>
<td>15.45</td>
<td>8.01</td>
<td>13.36</td>
<td>12.83</td>
<td>21.17</td>
</tr>
</tbody>
</table>

*Different superscript mark means significant differences.
allowed for dental restorations. Red and gray represent absolute errors in the \(X-Y\) plane and the \(Z\) axis measured for the 3D-printed samples, respectively. It can be found that absolute errors either in the \(X-Y\) plane or \(Z\) axis were lower than the maximum errors allowed for the oral restoration.

### 3.4 Tensile test results

The tensile test results are shown in Figures 8 and 9. The tensile test results showed that the tensile strength of the manual group is greater than that of the 3D-printed group. From the comparison within the group, the tensile strength and radial tensile strength of 3D-printing samples are very different, while the tensile strength and radial tensile strength of the manual group are not much different.

### 3.5 Surface analysis results

As shown in Figure 10, the SEM images of the polished sample surfaces and cross-sectioned surfaces are presented and compared. Group A-1.2 and Group B-1.2 were shown as representative samples.

The images of Group A-1.2 (Figure 10a) showed that there were few micro cracks on the 3D-printed resin sample surfaces (cracks were marked by arrow-1). Figure 10b (the particles were marked by arrow-2) and Figure 10e (the particles were marked by arrow-3) show that the particles could be observed clearly in both 3D-printed samples and hand-piled samples. Under the same mass ratio, the density of the hand-piled sample is higher than 3D-printed sample. The cross-section SEM images show that the schematic diagram of the internal organization of the material can also prove that different processing techniques caused density changes.

### 3.6 Density test results

The density of 3D-printed nano-ceramic sample with the ratio of NC:NF as 1.2:1 was tested as 1.92 \(\pm\) 0.06 g/cm\(^3\). The

*Different superscript mark means significant differences.

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**Table 4: Anisotropy hardness test results**

<table>
<thead>
<tr>
<th>Ratio (NC:NF)</th>
<th>1:1</th>
<th>1.1:1</th>
<th>1.2:1</th>
<th>1.3:1</th>
<th>1.426:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand piled (MPa)</td>
<td>180.39(^a)</td>
<td>202.25(^{a,b})</td>
<td>259.12(^b)</td>
<td>339.75(^{b,c})</td>
<td>377.24(^d)</td>
</tr>
<tr>
<td>(\pm SD)</td>
<td>14.33</td>
<td>13.70</td>
<td>13.91</td>
<td>11.82</td>
<td>17.05</td>
</tr>
<tr>
<td>3D printed (MPa)</td>
<td>237.63(^a)</td>
<td>289.32(^a)</td>
<td>333.67(^b)</td>
<td>405.44(^c)</td>
<td>450.11(^e)</td>
</tr>
<tr>
<td>(\pm SD)</td>
<td>13.45</td>
<td>11.01</td>
<td>12.57</td>
<td>12.09</td>
<td>18.45</td>
</tr>
</tbody>
</table>

*Figures 8 and 9: Anisotropy hardness comparison between hand-made and 3D printed, with a reference to the clinical requirement.*

**Table 5: Absolute error (\(\mu m\)) in Group A analyzed for the 3D-printed samples**

<table>
<thead>
<tr>
<th>Ratio (NC:NF)/accuracy</th>
<th>1:1</th>
<th>1.1:1</th>
<th>1.2:1</th>
<th>1.3:1</th>
<th>1.426:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>(X-Y) plane</td>
<td>0.076</td>
<td>0.051</td>
<td>0.054</td>
<td>0.030</td>
<td>0.060</td>
</tr>
<tr>
<td>Z axis direction</td>
<td>0.046</td>
<td>0.047</td>
<td>0.017</td>
<td>0.100</td>
<td>0.045</td>
</tr>
</tbody>
</table>

**Table 6: Relative error (\(\mu m\)) in Group A analyzed for the 3D-printed samples**

<table>
<thead>
<tr>
<th>Ratio (NC:NF)/accuracy</th>
<th>1:1</th>
<th>1.1:1</th>
<th>1.2:1</th>
<th>1.3:1</th>
<th>1.426:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>(X-Y) plane</td>
<td>0.017</td>
<td>0.013</td>
<td>0.013</td>
<td>0.007</td>
<td>0.015</td>
</tr>
<tr>
<td>Z axis direction</td>
<td>0.009</td>
<td>0.009</td>
<td>0.003</td>
<td>0.02</td>
<td>0.01</td>
</tr>
</tbody>
</table>
theoretical density of nano-resin materials is 1.95 g/cm³. The relative density of the 3D-printed nano-ceramic sample is therefore calculated as 98.4%, suggesting that high density has been achieved.

3.7 Printed dental crown

On the basis of the aforementioned experimental results, a dental crown made by printing with NC:NF ratio of 1.2:1 is shown in Figure 11, demonstrating the capability of the handcrafted DLP printer to achieve excellent contour profile and smooth surface using the nano-ceramic resin composite.

4 Discussion

4.1 Discussion on the viscosity test results

With the increase in the nano-ceramic resin mixing mass ratio, the viscosity increased as well (Figure 1). Because NC has the physical property of higher viscosity and lower flowability than NF nano-ceramic resin composites, the viscosity of the composite resin material is much higher than the printing parameters of 3D printers on the market. Therefore, we modify existing DLP printers to achieve directly 3D printing of nano-ceramic resins with high viscosity.

4.2 Discussion on the hardness obtained

Vickers hardness measurement is one of the most reliable methods to evaluate the physical properties of tooth hard tissue and dental restorative materials. In this study, the results of hardness (Figure 5) show that when the nano-ceramics resin composite NC:NF mass ratios were 1.2:1, 1.3:1, and 1.426:1, the 3D-printed nano-ceramic restorations (test samples) can meet the hardness requirements for oral prosthodontics. Meanwhile, the hardness value increased with the increase of filler proportion, in both the manual hand-piling group (Group B) and 3D-printing group (Group A). This is consistent with the previous study [22] that increasing the content of inorganic fillers will improve the mechanical properties of the dental resin composite materials, resulting in increased hardness.

When comparing between the 3D-printed group and the hand-piled group at the same NC:NF ratio, we found the hardness of the 3D-printed ones was slightly lower.
than the hand-piled ones. The reason is analyzed as follows.

In the hand-piling process, the resin material stacking process is divided into three layers. Each layer is cured by lamp for 20 s, and the thickness of each layer is 1.67 mm. In the case of the DLP processing, the whole 3D-printing process is divided into 100 layers, and the interval between the layers is 50 µm. In the micro indentation test, the hardness was measured by pressing a small, hard, and diamond-shaped indenter into the testing sample surface for certain dwell time. The height of the hardness probe used in this study is less than 1.67 mm. However, in Group A, the micro-indenter is pressed depth through several 3D-printed layers. The connection between layers cannot be very strong during the lay-by-layer printing procedure. We consider this might be one of the reasons that the hardness of 3D-printed sample was lower than that of the hand-piled sample at the same mass ratio.

In addition, to prevent the generation of air bubbles during hand piling, a certain amount of pressure is usually added. The compactness of hand-piled samples is better than that of 3D-printing samples, which can be demonstrated by SEM images. As shown in Figure 10(a), the imaging results of the different processes indicated that there were microcracks on the surface of the 3D-printed nano-ceramic restorations. There was a difference in surface integrity between the 3D-printed group and the hand-piled group (see Figure 10(c and f)). It implies that the compactness of hand-piled sample is higher than 3D-printed samples. For resin composite materials with a certain mass ratio, the better the compactness, the higher the hardness could reach. Therefore, it might be the second reason that hardness of the 3D-printing group is lower than that of Group B.

The hardness test results (Figure 6) of the reverse side showed that in the 3D-printing group, when the NC:NF mass ratio of the nano-ceramic resin composite material is 1.2:1, 1.3:1, and 1.426:1, the hardness of 3D-printed nano-ceramic restorations (test samples) could meet the requirements of oral restoration. When the NC:NF mass ratio of the nano-ceramic resin composite material is 1.3:1 and 1.426:1, the hardness of nano-ceramic restorations (test samples) of the manual group could also meet the requirements of oral restorations. When comparing the 3D-printing group and the manual group with the same NC:NF ratio, we found that the hardness of the 3D-printing group is better than the manual group. The reasons are as follows. The thickness of each layer of the 3D printing group is 50 µm, while the layer thickness of the manual group is 1.67 mm. When ultraviolet light is irradiated on the nano-porcelain resin, the intensity of the light is gradually weakened by the impact of the projection depth, and the light power that can be received at the bottom is attenuated, and the thicker the layer, the greater the light attenuation. The cured layer of nano-porcelain resin at the bottom gradually weakens. Manual group and the 3D-printing group have different light-curing methods, and this may also be a factor that affects the hardness. This will be demonstrated in our next study.

4.3 Discussion on the tensile obtained

Comparing Figures 8 and 9, we can find that the tensile strength of the manual group is greater than that of the 3D-printed group. From the comparison within the group, the tensile strength and the radial tensile strength of 3D-printing samples are very different, while the tensile...
Figure 10: SEM results. (a) 500 times surface picture by 3D printing (Group A-1.2, micro-cracks were marked by arrow-1). (b) 10,000 times surface picture from 3D printing (Group A-1.2, particles were marked by arrow-2). (c) 5,000 times imagination of cross-sectional surface by 3D printing (Group A-1.2). (d) 500 times surface picture from hand-made sample (Group B-1.2, polishing scratches were marked by arrow-3). (e) 10,000 times surface picture from hand-made group (Group B-1.2). (f) 5,000 times imagination of cross-sectioned surface by hand-made (Group B-1.2).
strength and radial tensile strength of the manual group is not much different. The main reason for the difference in radial and lateral mechanical properties is the lamina- tion and layer thickness. In this experiment, the layer thickness is 50 µm consistently. In the 3D-printing pro- cess, the three-dimensional data are discretized into layers in the early stage, and the two-dimensional plane data are then stacked according to the size of the layers, so the connection between each layer will directly affect the mechanical properties. This is shown in Figure 10c and f, and the molecules in the cross-section of the manual stacking are tighter, while the 3D-printing group is relatively loose.

4.4 Discussion on the accuracy obtained

Santoro et al. [23] compared the difference between the plaster model and the digital model and defined a clinically acceptable range of difference as 0.50 mm. Brand–Altman diagrams show that when deviations and accuracy are comparable to the previous products, they may be used clinically and interchangeably. Hazeveld et al. [24] used the Bland–Altman plots to compare the average systematic difference in clinical crown height measure- ment between the DLP model and the gypsum model. It is shown that errors between 0.20 and 0.50 mm can be used in clinical studies. The X–Y–Z measurements of the sam- ples in this study are all controlled using the high-precision VSM300 equipment, which can greatly reduce the distortion of the results due to measurement errors. As shown in Figure 5, comparing the measured values with those of the original digital model, the differences are statistically insignificant, all within 0.2 mm (Figure 7). Furthermore, the oral prosthesis manufactured by the DLP technology can meet clinical requirements in accu- racy. It needs to mention that hand piling uses no mold. Clinically, it is conducted according to the actual situa- tion, and hence, the resultant precision in not compar- able to the DLP technology.

5 Conclusion

Nano-ceramic resin dental prostheses made by hand- crafted DLP are considered clinically acceptable, in terms of geometry accuracy and mechanical properties.

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References


