In vitro investigation of the influence of printing direction on the flexural strength, flexural modulus and fractographic analysis of 3D-printed temporary materials

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The aim of this in vitro study was to evaluate the effect of printing direction and aging on the mechanical strength of 3D-printed temporary resin-based composites. Three hundred and sixty specimens (2x2x25 mm³) out of three materials were DLP printed. Specimens were either stored in distilled water for 24 h at 37°C or additionally subjected to thermocycling. Flexural strength (FS) and flexural modulus (FM) were evaluated in a three-point bending test considering three printing directions. Fractography was carried out by light microscopy, surfaces were categorized according to fracture origin. FS ranged from 93.2 to 159.9 MPa and 76.8 to 135.1 MPa in nonaged and aged specimens in the material sequence: Freeprint temp<Nextdentc&b<3Delta temp. Printing direction exerted a strong influence on 3Delta temp (p=0.042) and had an influence on fracture origin in Freeprint temp aged (p=0.009) and 3Delta temp (p=0.042) nonaged specimens. The effects of printing direction on FS were material dependent and lower than the effects of aging.

Keywords: 3D printing, Polymer materials, Flexural strength, Printing direction

INTRODUCTION

In the CAD/CAM sector, subtractive manufacturing has been shown to be the most successful and established manufacturing process in recent decades. Currently, it is considered the gold standard and a wide range of materials can be processed1. However, additive manufacturing (AM), also known as 3D printing, has recently gained relevance alongside subtractive manufacturing. The rapid development of AM methods in dentistry has been based primarily on the expiration of decisive patents in the field of 3D printing technology. As a result, several manufacturers have been able to optimize printers for the dental market, reduce hardware costs and introduce new materials. At present, AM technology is mainly used in dentistry to build models, implant templates, splints and temporary restorations2-5. Stereolithography (SLA) and digital light processing (DLP) technology are the most commonly used technologies in dentistry11. Both technologies work on the principle that an object is constructed layer by layer from a photopolymer. In SLA technology, a laser beam is directed via two mirrors to corresponding XY coordinates to polymerize the resin. DLP technology contains a microsystem and projects the light from the LED source as individual pixels onto the projection surface. While the advantages of AM, including material savings, independence of the milling instruments, geometrical freedom and combination of materials, are well known, the disadvantages are not widely addressed in dentistry. Mechanical property anisotropy and low filler content are the major flaws of AM due to the layered fabrication technique and have been investigated in research projects from various scientific fields6-14.

Primarily, anisotropy is a disadvantage; however, it can also be utilized in dentistry by adapting the printing direction of the restoration to the different load directions in the mouth. In the case of a molar, the bite force is preferably applied vertically, while a canine tooth is more exposed to transverse loadings. This can be taken into account by slicing the restoration in the CAM software in the corresponding manner of load direction. Osman et al. investigated the influence of the printing direction on the dimensional accuracy of full coverage restorations manufactured by DLP printing. They found significant differences in orientation of the object to the building platform where maximum deviation was observed at 90, 180 and 270 degrees15. However, there is a lack of evidence regarding how printing direction affects the mechanical properties of temporary materials.

Recently developed photopolymers for DLP technology are methacrylate-based resins that have been approved for temporary and midterm use for up to 2 years. They are particularly suitable for crowns, inlays, onlays, bridges and fixed tooth-colored splints16,17. One of the challenges of printing resins is their layered structure, leading to anisotropic mechanical properties7,9,18. Schaub et al. identified approximately 50 process variables that affect the printing process19. While most variables, such as the processing of the materials before printing, the printer used, the printing parameters, the layer thickness and the postprocessing, are specified by the manufacturers, there are no recommendations for the orientation and slicing of the object in the printing software. Understanding the effects of DLP printing direction on mechanical properties and the location of failure is important in assessing the performance of...
a restoration. Therefore, the aim of this study was to evaluate the effect of printing direction and aging on the flexural strength (FS) and flexural modulus (FM) of DLP 3D-printed temporary resin based composites and to perform fractographic analysis of the fractured specimens to enable better understanding of the involved fracture mechanism.

The tested null hypotheses were as follows: a) printing direction and b) aging have no influence on the mechanical properties and origin of fracture.

**MATERIALS AND METHODS**

*Preparation of samples*

The materials investigated and their chemical compositions are summarized in Table 1.

A computer-assisted STL file was created in the dimension of 2×2×25 mm³ and was imported into the CAM software Netfabb Premium 2019 (Autodesk, Mill Valley, CA, USA), where the samples were positioned and nested in two different directions to the building platform.

Two different printing modalities (Fig. 1A) and three different testing modalities (Fig. 1B), were considered:

1. Samples were printed in 2×25 mm³, Layers (XY-plane) with a Z building height of 2 mm. The force applied during testing was perpendicular to the layer orientation (Fig. 1a) named “horizontal parallel”.
2. Samples were printed in 2×25 mm³, Layers (XY-plane) with a Z building height of 2 mm and rotated by 90 degrees for testing. The force applied during testing was parallel to the layer orientation (Fig. 1b) named “horizontal perpendicular”.
3. Samples were printed in 2×2 mm³, Layers (XY-plane) with a Z building height of 25 mm. The force applied during testing was perpendicular to the layer orientation (Fig. 1c) named “vertical”.

Slicing was performed according to the manufacturer’s settings with a layer thickness of 50 µm for Freeprint temp and Nextdent c&b and of 100 µm for 3Delta temp. All groups (n=20) were manufactured by using a D20II DLP 3D printer (Rapidshape, Heimsheim, Germany) with the corresponding material printing parameters and postprocessing specifications. Specimens made of Freeprint temp and Nextdent c&b were cleaned for 5 min in an ultrasonic activated bath of 96% ethanol.

*Table 1 Brand names, manufacturers, composition (according to manufacturer) and batch numbers of tested materials*

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer</th>
<th>Lot number</th>
<th>Matrix</th>
<th>Inorganic filler</th>
<th>Content (wt%/vol%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nextdent c&amp;b</td>
<td>Nextdent, Soesterberg, the Netherlands</td>
<td>XK134N01</td>
<td>&gt;90 wt% Methacrylic oligomers, &lt; 3 wt% Phosphine oxides</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>3Delta temp</td>
<td>Deltamed, Friedberg, Germany</td>
<td>174909</td>
<td>Methacrylate</td>
<td>Siliziumdioxid, Dental glass</td>
<td>50/30</td>
</tr>
<tr>
<td>Freeprint temp</td>
<td>Detax, Ettlingen, Germany</td>
<td>200703</td>
<td>45-&lt;60 wt% Isopropylidenediphenol Peg-2 Dimethacrylat, 1.&lt;5 wt% 2 Hydroxyethylmethacrylat, 1.&lt;5 wt% Diphenyl(2,4,6 trimethylbenzoyl) phosphinoxid, 1.&lt;5 wt% Hydroxypropylmethacrylat, &lt;1 wt% Phenyl-bis(2,4,6-trimethylbenzoyl)-phosphinoxid</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
while 3Delta temp specimens were centrifuged for 3 min (Allegro X-15R, Beckmann-Coulter Life Science, Indianapolis, IN, USA) and rinsed subsequently with 96% ethanol. Freeprint temp and 3Delta temp were postcured for 2×2,000 flashes under a nitrogen atmosphere (Otolfash G171, NK Optik, Baierbrunn, Germany). Nextdent c&b specimens were postcured with LC-3D Print Box (Nextdent, Soesterberg, the Netherlands) for 30 min. Specimens were examined with a BMS 74956 light microscope (Breukoven, Essebann, the Netherlands) at 4.5-fold magnification for surface and edge defects, which could have been caused by printing error or detachment from the building platform.

Two different aging procedures were considered: (1) 1-day storage in distilled water at 37°C and (2) additionally followed by thermocycling (HaakeW15, Thermo Haake, Karlsruhe, Germany) between 5°C (±2) and 55°C (±2) for 10,000 cycles, with a dwell time of 30 s and a transfer time of 5 s.

**Micromechanical properties**

FS and FM were determined in a three-point bending test according to ISO 4049.

Samples were loaded until failure in a universal testing machine (Z 2.5, Zwick/Roell, Ulm, Germany) at a crosshead speed of 0.5 mm/min. The loading force was recorded as a function of specimen deflection. FS and FM were calculated according to the following equations:

\[
\sigma = \frac{3Fl}{2bh^2}
\]

\[
E_{\text{flexural}} = \frac{Fl^3}{4bh^3y}
\]

where \( F = \) maximum load (N), \( l = \) span between supports=20 mm, \( b = \) specimen width (mm), \( h = \) specimen height (mm), and \( y = \) deflection at the end of the linear part of the force-deflection diagram (mm).

### RESULTS

**Micromechanical properties**

The FS, FM and Weibull parameters are summarized in Table 2 and Figs. 2 and 3. 3Delta temp showed the highest significant FS and FM in aged and nonaged specimens. FS varied in the sequence of 3Delta temp>Nextdent c&b>Freeprint temp in all printing directions except

<table>
<thead>
<tr>
<th>Material</th>
<th>No Aging</th>
<th>Aged</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nextdent c&amp;b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallel</td>
<td>114.9 ( (9.0)^{ab} )</td>
<td>105.7 ( (7.7)^{ab} )</td>
</tr>
<tr>
<td>Vertical</td>
<td>111.9 ( (8.4)^{bc} )</td>
<td>101.2 ( (7.1)^{ab} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>No Aging</th>
<th>Aged</th>
</tr>
</thead>
<tbody>
<tr>
<td>3Delta temp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallel</td>
<td>159.9 ( (9.0)^{abc} )</td>
<td>143.4 ( (13.0)^{bc} )</td>
</tr>
<tr>
<td>Vertical</td>
<td>137.1 ( (7.8)^{bc} )</td>
<td>118.3 ( (12.1)^{bc} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>No Aging</th>
<th>Aged</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeprint temp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallel</td>
<td>100.5 ( (30.9)^{a} )</td>
<td>105.5 ( (113.8)^{a} )</td>
</tr>
<tr>
<td>Vertical</td>
<td>97.8 ( (11.5)^{a} )</td>
<td>98.7 ( (15.9)^{a} )</td>
</tr>
</tbody>
</table>

Small letters indicate statistically homogeneous subgroups for different printing directions within one material and aging. Large letters indicate statistically homogeneous subgroups for one printing direction and aging between different materials (\( p<0.05 \)).
nonaged horizontal parallel, and no significant difference between Nextdent c&b and Freeprint temp could be observed ($p>0.05$). No analyzed material achieved significantly higher values in the vertical printing direction compared to horizontally printed materials. 3Delta temp revealed significantly lower values for FS in the vertical printing direction compared to both horizontal printing directions ($p<0.05$). The parameter material exerted the highest influence on FS ($p<0.001$, partial eta-square $\eta^2_p=0.651$), followed by aging ($0.220$) and printing direction ($0.048$). The interaction effect of the combination of the independent parameter material and printing direction was also significant ($0.094$). The highest influence on FM was the material ($0.983$), followed by the parameter aging ($0.381$) and printing direction ($0.252$). The printing direction has the greatest influence within the materials on 3Delta temp for FS ($0.407$) and FM ($0.527$).

Freeprint temp exhibited the lowest reliability in aged and nonaged specimens (Fig. 3). The vertical printing direction induced the highest reliability directly after printing but the highest decrease in reliability after aging.

Fractographic analysis
Analysis of the fractured surface revealed differences in fracture mode (Table 3). 3Delta temp aged and Freeprint temp nonaged fractured more often at the edges located in both horizontal printing directions and surfaces located in the vertical printing direction. In Nextdent c&b and Freeprint temp, specimen fractures occurred in addition to the main fractures, which are referred to as secondary fractures. The chi-square test exhibited a significant relation between printing direction and fracture location (Table 4). Figure 4 shows an SEM image selection of fractured surfaces of different materials, printing directions, and fracture modes. Fracture patterns and fracture surface markings provide characteristic information for the materials.

Representative SEM micrographs that determine the filler composition are shown in Fig. 5. A variety of fillers in the resin composites were observed, and filler particle size and shape were material-dependent. Regarding particle dimensions, the largest particles observed were nonuniformly small-sized fillers in the range of one micron and less in the material 3Delta temp. The shapes of the submicron particles were irregular, and the interspaces were filled with smaller particles. In contrast, no fillers could be detected in Nextdent c&b and freeprint temp. The surfaces appear homogeneous, and the matrix is intersected by small cracks.
Table 3 Fractographic analysis of the different fracture origins before and after aging for different printing directions and materials (n=20)

<table>
<thead>
<tr>
<th>Material</th>
<th>Volume located</th>
<th>Edge located</th>
<th>Surface located</th>
<th>Sub Surface located</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>no aging</td>
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<td>no aging</td>
<td>aging</td>
</tr>
<tr>
<td>Horizontal parallel</td>
<td>3</td>
<td>2</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>Horizontal perpendicular</td>
<td>—</td>
<td>1</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>Vertical</td>
<td>3</td>
<td>4</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Volume located</th>
<th>Edge located</th>
<th>Surface located</th>
<th>Sub Surface located</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>no aging</td>
<td>aging</td>
<td>no aging</td>
<td>aging</td>
</tr>
<tr>
<td>Horizontal parallel</td>
<td>—</td>
<td>—</td>
<td>12</td>
<td>12</td>
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<tr>
<td>Horizontal perpendicular</td>
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<td>—</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>Vertical</td>
<td>—</td>
<td>1</td>
<td>5</td>
<td>6</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Volume located</th>
<th>Edge located</th>
<th>Surface located</th>
<th>Sub Surface located</th>
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</thead>
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<tr>
<td></td>
<td>no aging</td>
<td>aging</td>
<td>no aging</td>
<td>aging</td>
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<tr>
<td>Horizontal parallel</td>
<td>4</td>
<td>4</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Horizontal perpendicular</td>
<td>6</td>
<td>—</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Vertical</td>
<td>1</td>
<td>—</td>
<td>10</td>
<td>6</td>
</tr>
</tbody>
</table>

The quantities of secondary fractures caused by the reverberations of elastic waves once the primary fracture occurred are represented by the subscript numbers.

Table 4 Relationship between the printing direction and fracture location for material before and after aging (p<0.05)

<table>
<thead>
<tr>
<th></th>
<th>Nextdent c&amp;b</th>
<th>3Delta temp</th>
<th>Freeprint temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>no aging</td>
<td>0.476</td>
<td>0.042</td>
<td>0.341</td>
</tr>
<tr>
<td>aged</td>
<td>0.144</td>
<td>0.196</td>
<td>0.009</td>
</tr>
</tbody>
</table>

DISCUSSION

One of the main disadvantages associated with DLP/SLA printed temporary materials is their low filler content. According to the manufacturer, 3Delta temp contains 30% fillers by volume and 50% by weight. In Freeprint temp and Nextdent c&b, no fillers are specified by the manufacturer (Table 1). To evaluate a more precise composition of the materials, sputtered samples were analyzed by FE-SEM. The surface of Nextdent c&b and Freeprint temp appeared smooth compared to 3Delta temp, and no fillers could be detected. The FS of dental composites has been shown to improve with higher filler loading up to 60 vol%26-27. Therefore, the highest values for FS and FM in 3Delta temp might be attributed to its higher filler load. It is well known that the filler content shape, size distribution, silane treatment and mechanical properties also influence the viscosity of the composite28-30. Due to the fabrication of objects, especially by DLP/SLA printing technology, the viscosity of the uncured resin must be as low as possible to allow good recoating of the liquid monomer on the polymerized underlayer between the surface of the vat and the building platform31. In highly viscous DLP/SLA resin materials, gravity and surface tension are no longer able to produce a smooth surface, leading to processing defects, incomplete curing, voids and low accuracy23,31,32. A viscosity lower than ~5 Pas is a prerequisite in SLA and DLP printing at present to ensure satisfactory layer recoating33. Fractographic pictures revealed void formations of different sizes and locations (Fig. 4), which may be related to the viscosity of the resin. Voids were located mainly between two adjacent layers and rarely crossed the individual layers. Voids can act as flaws,
Fig. 4 Fracture surface SEM analysis, black arrows on the top of each picture indicate loading direction.

a) Horizontal perpendicular printed Freeprint temp specimen shows the surface fracture origin (O) located between printing layers (white arrows) (magnification 250×). b) Vertical printed Freeprint temp specimen shows the fracture origin edge; arrows indicate delamination (magnification 150×). c) Horizontal parallel printed Freeprint temp specimen shows the fracture origin (O), near-surface void between the first and second layer, fracture mirror (M), and hackle lines (H). Arrows indicate the direction of crack propagation. Dark arrow indicates delamination (magnification 250×). d) Horizontal perpendicular printed 3Delta temp specimen, compression, and protrusion of the initial layers (P) (magnification 250×). e) Horizontal parallel printed 3Delta temp specimen shows the fracture origin (O) at a surface void, fracture mirror (M), hackle lines (H), arrest lines (A), compression curl (CC). Arrows indicate the direction of crack propagation. The dotted arrow indicates a void inside the specimen (magnification 40×). f) Vertical printed Nextdent c&b specimen shows the fracture origin (O) volume location, fracture mirror (M), and hackle lines (H). Arrows indicate the direction of radial crack propagation, and dotted arrows indicate delamination (magnification 40×). g) Horizontal parallel printed Nextdent c&b specimen; white lines indicate different printing layers; arrows indicate void inclusions between layers (magnification 150×).

Fig. 5 SEM of sputtered specimens at a magnification of 10,000× for Nextdent c&b (a), 3Delta temp (b) and Freeprint temp (c).

There are different manners in which voids can access the DLP/SLA printed object before or during the printing process. Resin composites used for DLP/SLA printing are usually supplied by the manufacturers in bottles. To ensure a homogeneous material during the printing process, the resin composites are stirred or shaken according to the manufacturer’s instructions and then poured into the vat of the DLP/SLA printer. This process may result in the accumulation of voids since this is done under atmospheric pressure. Nitrogen inerting or mixing under vacuum before pouring the resin into the vat can be successfully used to overcome void inclusion in some instances. In addition, voids can enter the DLP/SLA printed objects in a process-related fashion. After the polymerization of a layer, the building platform is detached from the bottom of the vat, and a generated negative pressure causes air to enter the resin. The exhaustion of dissolved voids has been shown to be dependent on the viscosity of the resin and decreases with increased resin viscosity; therefore, a low-viscosity resin can enhance the isotropy of printed SLA/DLP parts.

The layer thicknesses in which the materials are printed differ from each other and can influence the degree of anisotropy. Interlayers have been shown to be the weakest links and can easily be separated by volume-induced fractures.

even if they are located in the interior of the specimen, and may act as fracture origins. The void fraction was identified as a determinant factor in the mechanical performance of resin composites, which may reduce the interfacial bonding layers and lead to delamination and
interfacial shear loads\textsuperscript{40,37}. While the manufacturer sets the thickness at 100 µm for 3Delta temp, Nextdent c&b and Freeprint temp are printed at a 50 µm thickness. The total area of the interface between the layers is thus half for 3Delta temp because of the number of printing layers. The risk of a possible printing error or void inclusion that could result in a volume-caused fracture is thus reduced by printing with a 100 µm layer size. This is also supported by the fact that voids have been located in the SEM images mainly between the 2D layers of the samples (Fig. 4) and is in line with previous studies\textsuperscript{19}. Consequently, the anisotropy of 3Delta temp can be described as lower because of the 100 µm layer size. The latter has been identified by studies before evaluating the influence of different layer thicknesses on mechanical properties and their anisotropy\textsuperscript{18,38}. Dizon et al. even determined in their study that the layer thickness has a larger impact on the strength of the object than the printing direction\textsuperscript{49}.

Each resin manufacturer defines specifications for the printer hardware, printer software, printer parameters, and postprocessing to achieve an optimal result. A limitation of the study is that the materials were printed according to IFK. In the present study, an open DLP printer with a wavelength of 385 nm was used to minimize the error. This printer is validated by the manufacturers for all used materials by means of corresponding print parameters. Further we hypotheses, that there would be changes in the material properties, if an SLA printing device would be used. Due to the difference way of polymerization in previous studies it could be observed an impact of printing technologies. Unfortunately, the temporary resin composites used in this study were not approved for the SLA.

The aging protocol used in this study concerned thermal aging proposed in ISO 11405 recommendations with a thermal regime between 5°C and 55°C. Gale and Darvell postulated that the 10,000 thermal cycles used correspond to 1 year of clinical function and are in the time range of the clinical use of temporary materials\textsuperscript{40}. Aging can lead to component leaching, swelling and degradation of the cross-linked matrix and hydrolysis of the filler-matrix interfaces, resulting in the decline of mechanical properties and plastification\textsuperscript{41-43}. This fact was confirmed by the present study via the decline in FS and FM for all materials after aging and by fractographic analysis.

After the aging of the Nextdent c&b and Freeprint temps, a smooth and inconspicuous appearance can be seen at the fractured surfaces (Fig. 4). Typical brittle fracture patterns are rare, which implies a lower fracture energy. After the initial fracture, the intense stored elastic energy in the specimen is released, sending stress waves through each fractured part. Reverberations and tension reflections can cause additional breakages defined as secondary fractures\textsuperscript{44}. 3Delta temp revealed significantly inferior values for FS in the vertical printing direction compared to the two horizontal printing directions \((p<0.05)\). The three-point bending test subjected the sample to significant tensile and compressive stresses, which vary from zero at the neutral axis to the maximum at the outermost surfaces. In the vertical printed samples, the force on the tensile zone causes a separation at the individual printed 2D layers, providing an easy path for crack propagation and absorbing the lowest amount of energy. The observed failure between the layers at the vertical printed samples tends to be more catastrophic for fractures because they could be easily separated by interfacial shear loads. These observations are consistent with previously published data showing an advantage for parallel printed samples\textsuperscript{7,10,13,45}. As a result, the different printing directions have also designated as (a) crack divider, (b) crack arrester and (c) crack splitting/short transverse\textsuperscript{12,45,46}. It was also assumed that in the horizontal parallel (crack arrester) direction, each printed layer acts as an impediment to total fracture. The crack must first break one layer and begin again on a subsequent layer until the final fracture occurs\textsuperscript{10}. This effect is more pronounced with stronger materials such as 3Delta temp than for Freeprint temp and Nextdent c&b. Accordingly, the printing direction has the greatest influence on 3Delta temp at \(\eta_p=0.407\) for FS and \(\eta_p=0.527\) for FM. This hypothesis is also supported by fractography, where the vertically printed 3Delta temp specimens fracture more frequently at the surface in comparison to the horizontally printed specimens. The chi-square test revealed a significant relation between printing direction and fracture location for non-aged 3Delta temp specimens. In the vertically printed samples, fractures between the layers and delamination could be observed more often. The horizontal parallel samples broke more often at the edges for all materials. An additional contributing factor is that the specimens of vertically printed materials have rounder edges according to SEM observations (Fig. 4), and thus fractures located at the edges may be reduced. The rounded edges in vertically printed specimens could be due to the different resolution of the printing axis. The resolution in the different planes is characteristic for a DLP/SLA printer and a possible explanation for the different edge angles at the outer areas. Bablani and Bagchi therefore suggested that curved surfaces should be oriented in the horizontal plane for higher surface resolutions\textsuperscript{47}. All specimens were measured in the middle and at the marginal area, and the tolerable deviation was set to ±0.1 mm. The cross-sectional differences between the printing directions of the specimens should therefore have a negligible influence on the FS. Further characteristic printing phenomena underlining the anisotropy can be observed in the SEM images of the parallel printed samples. The first layers require a particularly strong adhesion to the building platform; therefore, additional exposure and compression are carried out. This compaction leads to a shortened layer distance and protrusion in width (Fig. 4).

Although the printing direction revealed a significant effect on FS and FM, with values of \(\eta_p=0.048\) and \(\eta_p=0.252\), the choice of material exerts the highest influence, followed by aging.
A Weibull analysis relates the strength of each of the tested specimens to the probability of failure, thus providing the Weibull modulus as a measure of material reliability. This provides more detailed information for predicting the failure stress of composite materials compared to the average FS and associated standard deviations alone.

A higher Weibull modulus is represented by steeper slopes of fit lines in Fig 3 and reflects a higher consistency (less scattering) of strength values at which individual specimens failed, thus implying better material predictability. Higher m, also in combination with slightly lower average fracture strength, is often preferable to lower m in combination with higher average fracture strength(48). Freeprint temp showed the lowest deviations alone.

For predicting the failure stress of composite materials providing the Weibull modulus as a measure of material reliability. This provides more detailed information as varied. The reliability can be reduced by water but can also remain unaffected by artificial aging(49). In our study, the Weibull modulus increased in the horizontal perpendicular printing direction and diminished in the vertical printing direction throughout the aging process in all materials.

CONCLUSION

SEM images, fractography and the FS and FM results revealed a certain anisotropy in the test specimens. This study highlights that the printing direction of the samples has a significant influence on the mechanical properties and that this must be taken into account by nesting and slicing the restorations in CAM software. The three-point bending test induces tensile and compressive stresses in the specimens being tested, which can cause the low-strength interfaces between the 2D layers to delaminate before the 2D layers fracture. An alignment of the layers perpendicular to the direction of the load is preferred. However, the material itself had the greatest influence on FS and FM, followed by aging and printing direction. In view of these results, a material with a higher filler content is recommended for printing temporary restorations. Thus, all the tested null hypotheses can be rejected.

REFERENCES