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Original Article

Impact of printing layer thickness on the flexural strength of nanocomposite 3D printed resins: An in vitro comparative study

Mohammed M. Gad [a,*], Fatimah Abdullah Alzaki [b], Fatimah Ahmed Abuwarwar [b], Ali Alhammad [b], Mohammed Al Hussain [b], Soban Q. Khan [c], Essam A. Nassar [d], Neveen M. Ayad [e]

[a] Department of Substitutive Dental Sciences, College of Dentistry, Imam Abdulrahman Bin Faisal University, P.O. Box 1982, Dammam 31441, Saudi Arabia
[b] College of Dentistry, Imam Abdulrahman Bin Faisal University, P.O. Box 1982, Dammam 31441, Saudi Arabia
[c] Department of Dental Education, College of Dentistry, Imam Abdulrahman Bin Faisal University, P.O. Box 1982, Dammam 31441, Saudi Arabia
[d] Department of Preventive Dental Sciences, College of Dentistry, Imam Abdulrahman Bin Faisal University, P.O. Box 1982, Dammam 31441, Saudi Arabia
[e] Department of Restorative Dental Sciences, College of Dentistry, Imam Abdulrahman Bin Faisal University, P.O. Box 1982, Dammam 31441, Saudi Arabia

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ABSTRACT

Background: This study evaluated the influence of various printing layer thicknesses with silicon dioxide nanoparticles (SiO_2NPs) incorporated as a reinforcement material on the flexural strength of 3D-printed denture base resins.

Material and Methods: Asiga (DentaBASE, Asiga, Erfurt, Germany) and NextDent (Denture 3D+, NextDent B.V., Soesterberg, The Netherlands) 3D-printed resins were modified with different concentrations of SiO_2NPs (0.25 % and 0.5 wt%). A total of 180 specimens (bar-shaped, 64 × 10 × 3.3 mm) were fabricated (N = 90/resin). Each resin was subdivided into three groups (n = 30) according to the SiO_2NP concentration (0 %, 0.25 %, and 0.5 wt %) Each concentration was divided into three groups (n = 10) according to the printing layer thickness (50 μm, 75 μm, and 100 μm). Specimens were printed according to the manufacturer's instructions and then subjected to 10,000 thermal cycles. A three-point bending test was used to measure the flexural strength (MPa). One-way analysis of variance (ANOVA) and Tukey's post hoc tests were used to analyze the data (α = 0.05).

Results: For both resins, printing layer thicknesses of 50 μm and 75 μm exhibited significantly higher flexural strength than 100 μm ($P < 0.001$). The 50 μm thickness showed the greatest flexural strength values (81.65 ± 4.77 MPa and 84.59 ± 6.21 MPa for Asiga and NextDent, respectively). The 100 μm thickness showed the lowest flexural strength values (74.35 ± 5.37 and 73.66 ± 5.55 MPa) for Asiga and NextDent, respectively. The flexural strength significantly increased with the addition of SiO_2NPs with printing layer thicknesses of 50 μm and 75 μm ($P < 0.001$), whereas the modified and unmodified groups printed with a 100 μm layer thickness did not differ significantly. Asiga 0.25 %/50 μm and NextDent 0.5 %/50 μm showed the highest flexural strength values (97.32 ± 6.82 MPa and 97.54 ± 7.04 MPa, respectively). Scanning electron microscopy fractured surfaces analysis revealed more lamellae and irregularities with lower printing layer thicknesses and SiO_2NP concentrations.

Conclusion: The flexural strength increased with printing layer thicknesses of 50 μm or 75 μm combined with SiO_2NP reinforcement.

1. Introduction

Since computer-aided design (CAD) computer-aided manufacture (CAM) technology was introduced in dentistry, it has gradually become an excellent option for denture construction. CAD-CAM technology possesses several advantages, including fewer visits, reduced laboratory work and chair time (Clark et al., 2019), and the adaptability and accuracy of the fabricated denture base (Yoshidome et al., 2021, Grande et al., 2022). Two main methods are used for digital denture fabrication; the subtractive method (SM) and the additive method (AM). The SM involves milling the prefabricated acrylic resin disc to the required design, whereas the AM builds an object layer-by-layer using

* Corresponding author.
E-mail address: mmjad@iau.edu.sa (M.M. Gad).

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photopolymerized fluid resins in a process called 3D printing (Gad et al., 2022a).

Despite the wide variety of 3D-printing systems, materials, modifications, fabrications, and facilities, the mechanical performance of the AM is questionable compared with that of the SM and conventional fabrication methods for denture base resins (Prpić et al., 2020). In general, 3D-printed denture base materials show low mechanical properties compared with conventional denture base materials (Gad et al., 2022a, Freitas et al., 2023). Previous studies (Prpić et al., 2020, Gad et al., 2022a, Freitas et al., 2023, Zeidan et al., 2023) compared 3D-printed resins with AM and conventionally fabricated resins and reported that 3D-printed resins had low strengths—lower than the recommended ISO strength (65 MPa). This weakness was mainly attributed to the printing method (layer-by-layer) and the weak bond between subsequent layers, along with the photo-polymerization method with the increased amount of residual monomer (Prpić et al., 2020, Gad et al., 2022, Gad and Fouda, 2023).

Many factors affect the strength of printed resins; these factors are classified into pre-printing, printing, and post-printing factors (Gad and Fouda, 2023). Pre-printing refers to the resin modifications before printing via reinforcing nanoparticles and the addition of antifungal agents (Altarazi et al., 2023, Aati et al., 2022, Khattar et al., 2023). Printing factors focus on various parameters, namely orientation, layer thickness (LT), supporting structures, position, and light intensity (Liu et al., 2021, Gad and Fouda, 2023). Post-curing factors are mainly for further polymerization, with different conditions such as rinsing solutions, rinsing time, curing time, curing temperature, and post-curing devices (Li et al., 2021, Gad and Fouda, 2023). The use of one of these factors or combinations between two or more factors was suggested to improve the strength of 3D-printed resins (Li et al., 2021).

Recent studies (Alshaikh et al., 2022, Gad et al., 2022b) have shown that nanoparticles affect the surface hardness, surface roughness, impact strength, and flexural strength of 3D-printed resins used to fabricate denture bases. One study incorporated zirconium dioxide nanoparticles into 3D-printed resins used for denture bases and showed no significant differences in surface roughness; however, the results showed significant increases in impact strength, hardness, and flexural strength (Alshaikh et al., 2022). Another study added silicon dioxide nanoparticles (SiO_2NPs) at different concentrations to the 3D-printed denture base with a 0.5 % concentration; this led to an improvement in mechanical properties (increased hardness, impact strength, and flexural strength) compared with unmodified 3D-printed resin (Gad et al., 2022b).

Several studies have explored the influence of the printing LT on the mechanical properties of 3D-printed products (Liu et al., 2021, Lee et al., 2022, Farkas et al., 2023). An investigation by AlShammrani et al. revealed that specimens printed with a 100 μm thickness showed a greater flexural strength value than those printed at 25 μm and 50 μm (Alshamrani et al., 2022); the authors concluded that both the LT and the printing layer direction can affect mechanical properties. Another investigation revealed that higher tensile values were achieved with a printing LT of 50 μm than with a thickness of 100 μm (Farkas et al., 2023). Lee et al. found that for 3D-printed dental resins, the color stability and surface characteristics could be affected by changing the printing LT (Lee et al., 2022).

Furthermore, several types of nanoparticles have been incorporated into 3D-printed denture bases, such as SiO_2NPs at different concentrations; as previously mentioned, this has led to a significant improvement in 3D-printed resin properties. However, the effect of adding nanoparticles has not been explored with different printing LTs. Therefore, this study investigated the effect of SiO_2NPs and printing LT on the flexural strength of 3D-printed resins. The null hypothesis was as follows: the addition of SiO_2NPs with different 3D printing LTs does not affect the flexural strength of 3D-printed resins.

2. Materials and methods

2.1. Sample size calculation

Power analysis was performed to determine the sample size for this in vitro study. The World Health Organization (WHO) formulae were used; the power was set at 80 %, the significance level was set at 5 %, and the marginal error was set at 5 % (Chen et al., 2019). The number of samples was determined to be 10 per group.

2.2. Nanocomposite mixture and preparation

Fig. 1 summarizes the 3D-printed resins, SiO_2NPs, and their printing specifications. For every resin group, a silane coupling agent (3-trimethylsilyl methacrylate, 97 % Y-MPS) was used to treat SiO_2NP surfaces, following the method detailed in a previous study (Alzayyat et al., 2022). Regarding SiO_2NP addition, one group remained unmodified, and the other two groups were modified with two different concentrations; one group was modified with 0.25 %, and the other was modified with 0.5 wt%. For resin content distribution, the resin container was placed on a shaker and shaken for 1 h. An electronic balance was used for the resin/SiO_2NP proportion and addition, followed by vigorous mixing to ensure a normal distribution of nanoparticles within the fluid resin. To produce the nanocomposite for the 3D-printed denture base resin, each container was then stirred on a magnetic stirrer for 30 min for a homogenous distribution of SiO_2NPs (Alshaikh et al., 2022).

2.3. Specimen design and printing

Bar-shaped specimens (64 × 10 × 3.3 mm) were designed according to the ISO 20795–1: 2013 standard (Alshaikh et al., 2022). To create a Standard Tessellation Language (STL) file with the required dimensions, a CAD program (123D Design, Autodesk version 2.2.14, CA) was utilized. STL files were imported to each printer system (Asiga and NextDent). The specimens were designed with an appropriate number of supports. Printing was completed according to the printing parameters in Fig. 1. Every concentration group per 3D-printed denture base was printed in three different LTs (50 μm, 75 μm, and 100 μm). Once the specimens were printed, they were cleansed with isopropyl alcohol (99.9 %) and underwent further polymerization with the required post-curing conditions (Fig. 1).

Supports were removed using a low-speed acrylic bur, and finishing was achieved with silicon-based carbide grinding paper. The sequence was as follows: 800-grit, 1500-grit, and 2000-grit. After all specimens were finished, they were rinsed with water (Gad et al., 2022a). A polishing cloth was used in a polishing machine (MetaServe 250 grinder-polisher, Buehler GmbH) under wet conditions to polish all the specimens (Kwon et al., 2021). To mimic one year of function in the oral environment, all printed specimens underwent thermal aging for 10,000 cycles (each cycle at 5 °C to 55 °C with a dowel time of 30 s) using a thermocycling machine (THE-1100 Thermocycler, SD Mechatronik GMBH, Pleidelsheim, Germany) (Gad et al., 2022b).

2.4. Specimens testing

A universal testing machine (Instron Model 8871, Instron Corp., Norwood, MA, USA) was used to measure the flexural strength using a 3-point bending test. Each specimen was positioned and centered on a customized jig with 50 mm between the two supports. To measure the fracture force in Newtons (N), each specimen was exposed to 50 KN load at its center at a cross-head speed of 5 mm/min until failure. The flexural strength (MPa) was calculated using the equation $FS = 3Fl/2bh^2$, where F is the maximum load (N), l is the length of the support span (mm), b is the width (mm) of the specimen, and h is the height (mm) of the specimen.

Specifications	Resins	
	ASIGA	NextDent
Brand name	DentaBASE ASIGA, Erfurt, Germany	Denture 3D+ NextDent B.V., Soesterberg, The Netherlands
Compositions	Ethoxylated bisphenol A dimethacrylate 7,7,9 (or7,9,9)-trimethyl-4,13-dioxo-3,14-dioxa-5,12-diazahexadecane-1,16-diyl bismethacrylate 2- hydroxyethyl methacrylate silicon dioxide diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide, titanium dioxide	Ester-based monomer; Bisacylphosphine oxide (BAPO) phenylbis (2, 4, 6-trimethylbenzoyl)-phosphine oxide (Omnirad 819)
Resin modifications	Silicon dioxide nanoparticles [(AEROSIL R812; Evonik Degussa, Germany) white color; 99.5% purity; average size: 15nm;specific surface area: 150–550 m^2/g; and density: 2.2 g/cm^3] Incorporated in two concentrations 0.25%, and 0.5%wt.	
Shaker	3D system, Vertex dental B. V. Soesterberg, Netherland	
Printer	ASIGA MAX™	NextDent 5100
Printing orientations	90-degree	
Printing layer thickness	50µm, 75µm, 100µm	
Post-curing conditions	3D system, Vertex dental B. V. Soesterberg, Netherland, 10 minutes/ 45°C	ASIGA Flash 20 minutes/ 65°C
Finishing and polishing	Support removal and followed by finishing and polishing	
Thermal cycling	10.000 thermal cycles simulating 1 year clinical use	

Fig. 1. Materials specifications and machines used for specimens fabrications.

2.5. Statistical analysis

Statistical Package for Social Sciences (SPSS v. 23) was used to statistically analyze the data. The Shapiro–Wilk test was used to assess data normality; insignificant results revealed normally distributed data. Hence, inferential data analysis was performed with a parametric test. One-way analysis of variance (ANOVA) was utilized to assess the effects of the LT and the concentration of nanoparticles on flexural strength. Pairwise comparisons were carried out with Tukey's post hoc tests. Finally, two-way ANOVA was used to determine the effect of both the printing LTs and SiO_2NP concentration on flexural strength. P-values of less than 0.05 were considered statistically significant.

3. Results

The means, standard deviations, and significance of the Asiga resin are shown in Table 1 with both variables: LT and SiO_2NP concentration. The ANOVA results revealed significant differences between groups ($P < 0.001$). In the pairwise comparison, the 50 µm LT and 75 µm LT groups showed the highest values for flexural strength, with no significant difference between groups ($P > 0.05$); however, we observed a significant decrease in flexural strength in the 100 µm LT group ($P < 0.001$). Compared with the unmodified group, the addition of SiO_2NPs (at both concentrations) in the 50 µm LT and 75 µm LT groups showed an increase in flexural strength values ($P = 0.001$), with no significant difference between the 50 µm LT and 75 µm LT groups ($P > 0.05$). In the 100 µm LT group, no significant difference was found with the addition of SiO_2NPs ($P = 0.093$).

Table 1 shows the means, standard deviations, and significance of the NextDent resin with both variables: LT and SiO_2NP concentration. The ANOVA results showed a significant difference between groups ($P < 0.001$). In the pairwise comparison, the 50 µm LT and 75 µm LT groups showed the highest values of flexural strength, with no significant difference between groups ($P > 0.05$); however, in the 100 µm LT, showed a significant decrease in flexural strength ($P < 0.001$). Compared with the unmodified group, the addition of SiO_2NPs (both concentrations) at 50 µm LT and 75 µm LT showed an increase in the flexural strength values ($P = 0.001$), with no significant difference between concentrations ($P > 0.05$). In the 100 µm LT group, no significant differences were found between groups with different concentrations of SiO_2NPs ($P = 0.072$).

The combined effect of LT and nanoparticle addition was analyzed using two-way ANOVA (Table 2). We detected a significant difference when analyzing the combined effect of the printing LTs and the nanoparticle concentration ($P = 0.03$).

Table 1
Mean, SD of flexural strength (MPa) of tested resin materials and significant between groups in term of printing layer thickness and SiO_2NPs concentrations.

3D printed resins	SiO_2NPs %	Thickness			
		50 µm (Mean ± SD)	75 µm (Mean ± SD)	100 µm (Mean ± SD)	P value
Asiga	Pure	81.65 ± 4.77[a]	81.56 ± 3.76[a]	74.35 ± 5.37	P < 0.001
	0.25 %	97.32 ± 6.82[a,A]	95.63 ± 4.27[a,A]	78.13 ± 4.97	P < 0.001
	0.5 %	95.55 ± 5.11[a,A]	94.06 ± 3.44[a,A]	75.8 ± 7.23	P < 0.001
	P value	P < 0.001	P < 0.001	P = 0.093	
NextDent	Pure	84.59 ± 6.21[a]	83.33 ± 5.09[a]	73.66 ± 5.55	P < 0.001
	0.25 %	94.59 ± 6.98[a,A]	90.76 ± 4.92[a,A]	79.66 ± 4.02	P < 0.001
	0.5 %	97.54 ± 7.04[a,A]	93.55 ± 4.88[a,A]	75.55 ± 3.33	P < 0.001
	P value	P < 0.001	P < 0.001	0.072	

Same small letter horizontally indicating non-significant differences between groups. Same capital letter vertically per resin indicating non-significant differences between groups ($P > 0.05$).

Table 2
Combined effect of layer thickness and nanoparticles concentrations using Two-way ANOVA.

Source of variation	Sum of Squares	df	Mean Square	F	p
Layer thickness (LT)	283.221	3	145.172	4.750	<0.001
NP%	1923.825	7	3305.969	106.543	<0.001
Layer thickness (LT) * NP%	438.403	13	37.543	1.211	0.03
Error	5707.494	143	32.348		
Total	24505.810	212			

4. Discussion

This study investigated the effects of different printing LTs and the addition of different concentrations of SiO_2NPs to two 3D-printed resins on the flexural strength. The results did not support the null hypothesis, as the flexural strength values of the unmodified 3D-printed resins differed significantly from 3D-printed resins modified with different concentrations of SiO_2NPs and different printing LTs.

Denture base fracture is the most common failure type that both prosthodontists and patients are concerned with (Stafford and Smith, 1970, Kelly, 1969, Takahashi et al., 2012). The most common cause of denture base fracture is flexural fatigue due to repeated normal masticatory forces or abnormal jaw activities, such as bruxism, which is a repeated movement of the jaw characterized by the teeth clenching against each other and/or the thrusting of the mandible (Kelly, 1969, Takahashi et al., 2012). This causes the accumulation of stress and hence microcrack propagation through the denture base, leading to fatigue failure over time (Stafford and Smith, 1970). Therefore, it is crucial for denture bases, especially those constructed by 3D printing, which have poorer mechanical properties than conventionally constructed ones, to possess high flexural strength to endure such stress and survive throughout their use without bending, which can ultimately result in the midline fracture of the denture base (Prombonas and Vlissidis, 2006).

Digital light processing (DLP) and stereolithography (SLA) technologies are the two most common 3D printing techniques for constructing dental prostheses (Simeon et al., 2024, Jeong et al., 2023). For both techniques, a photopolymerizable resin is used to build the object in successive layers. The activation of the polymerization initiators, either by light flashed from a digital projector screen through the whole layer in DLP or by the laser light track in SLA, lead to the liberation of free radicals that interact with the resin monomers and oligomers and convert them into the resin polymer (Jeong et al., 2023). The degree of the conversion of the carbon double bonds in the monomers into single bonds to form the polymer chains has a directly proportional effect on the flexural strength of the built object (Borella et al., 2023). The greater the intensity and amount of light that passes through the polymerizing layers, the higher the degree of conversion and chain crosslinking and the lower the residual monomer, thus increasing the 3D-printed object's flexural strength adequately to withstand the stresses resulting from chewing forces or oral parafunction (Gad and Fouda, 2023).

As mentioned previously, several studies concluded that PMMA modified with different nanoparticles displayed a significant improvement in flexural strength (Zidan et al., 2020, Aati et al., 2022, Alshaikh et al., 2022). Zidan et al. measured the flexural strength of removable complete dentures that were constructed from zirconia-impregnated PMMA nanocomposites to judge their mechanical performance (Zidan et al., 2020). For the abovementioned reasons, the mechanical behavior of 3D-printed resin was evaluated by determining its flexural strength after the addition of various concentrations of SiO_2NPs using different LTs (Zidan et al., 2020).

Thermal changes in the oral environment adversely affected the resin denture base material's mechanical properties. This was due to water sorption by resins when immersed in the fluids. The absorbed water resulted in the plasticizing effect and the deterioration of the mechanical properties (Radford et al., 1997, Lin et al., 2000, Gad et al., 2022a). The amount of water sorption increased when the surrounding temperature increased, subsequently resulting in more deterioration of the resin properties (Gad et al., 2022b). To obtain reliable results, the tested materials were exposed to 10,000 thermal cycles to mimic 1 year of function in the oral environment (Radford et al., 1997, Gad et al., 2022b).

In this study, three printing LTs were used (50, 75, and 100 μm) for both Asiga and NextDent 3D-printed denture base resins. Statistical analysis revealed the lowest flexural strength value for the 100 μm LT; however, it was still above the accepted ISO value, which is 65 MPa (International Organization for Standardization, 2013). For both tested 3D-printed resins, the flexural strength values were significantly higher for the 50 μm LT, and those of the 75 μm LT were significantly higher than those of the 100 μm LT, but with no significant difference between the 50 μm LT and the 75 μm LT. The lower flexural strength value obtained with the 100 μm LT could be attributed to two factors. First, according to a previous study, during the photopolymerization process, thicker printed layers include more voids with larger sizes than those formed with thinner printed layers. The increased number and size of the formed voids resulted in less dense polymers and thus lower strength values compared with those of thinner printed layers due to the higher possibility of stress concentration and hence the reduced ability to withstand high stress levels before failure or fracture by three-point bending, as explained in another study, indicating lower flexural strength (Chockalingam et al., 2006, Farkas et al., 2023). Second, the lower flexural strength could be attributed to the photopolymerization process of 3D-printed resins itself, which utilized light instead of heat compared with conventional resins. The use of light may lead to a lower degree of fluid monomer to polymer conversion, which could result in residual unpolymerized monomer. Residual monomer could act as a plasticizer for the obtained 3D-printed resin, with an adverse effect on its mechanical properties, including flexural strength (Reymus et al., 2019, Zeidan et al., 2023). Moreover, a higher printing LT led to a higher possibility of hindering the polymerizing light from penetrating and converting monomer into polymer, with a subsequent decrease in flexural strength values. The findings of the current investigation align with those of other studies, which concluded that the thinner printing layers provided higher mechanical properties (Reymus et al., 2019, Liu et al., 2021, Farkas et al., 2023). On the other hand, these results conflict with the findings of another study on a 3D-printed resin, which found that 100 μm LT resin had higher flexural strength than the other lower-thickness groups. These results might be due to post-printing treatment conditions, including the application of heat, which directly causes an increase in the conversion of monomer into polymer and thus increases the flexural strength (Alshamrani et al., 2022).

A significant increase in the flexural strength values was displayed for the SiO_2NP-modified Asiga and NextDent 3D-printed resins compared with the unmodified resins. These results agree with those of previous studies that incorporated metal oxide nanoparticles in the tested materials, such as ZrO_2NPs into 3D-printed resins, nanodiamonds into provisional resins, and different metal oxide nanoparticles into denture base materials (Karci et al., 2019, Mangal et al., 2020, Aati et al., 2021). All groups showed increased flexural strength values compared with the unmodified comparison groups. This can be explained by the ability of metal oxide nanoparticles to act as reinforcing agents by the dispersion strengthening of the resins, thus interrupting crack propagation and increasing their flexural strength (Gad et al., 2017). According to a recent study, adding low concentrations of SiO_2NPs imparted an increase in the mechanical properties of the 3D-printed denture base resin, so 0.25 % and 0.5 % SiO_2NP concentrations were selected for the present investigation (Gad et al., 2022b). These low concentrations of SiO_2NPs resulted in their homogenous distribution within the polymer chains and subsequent dispersion strengthening without unfavorable agglomeration in the form of nanoclusters, which, if formed, could weaken the resin by separating the polymer chains (Gad

et al., 2017, Karci et al., 2019, Gad et al., 2022b). Both the 0.25 % and 0.5 % concentrations of SiO_2NPs were low enough to avoid the formation of the detrimental agglomerated clusters; hence, both resulted in an increase in the flexural strength values but without a significant difference between groups.

The results of this investigation demonstrated that the addition of SiO_2NPs at concentrations of 0.25 % and 0.5 % to Asiga and NextDent 3D-printed resins was most effective in increasing the flexural strength when combined with low printing layer thicknesses of 50 or 75 μm. This may be explained by the collective strengthening action of the homogenously distributed low concentration of SiO_2NPs in the polymer chains, together with the deep penetration of polymerizing light through the thin printing layers, which resulted in the adequate photopolymerization of the fluid resin into a polymer with a high degree of conversion and less residual monomer. As previously mentioned, printing thin layers is theorized to result in fewer, smaller-sized voids that may form during the photopolymerization process. This could ultimately result in a denser polymer with a lower possibility of stress concentration and hence a greater ability to withstand higher stress levels before failure or fracture by three-point bending, indicating higher flexural strength compared with that of thicker printing layers (Chockalingam et al., 2006, Farkas et al., 2023).

To the best of the authors' knowledge, the combined impact of printing layer thickness and nanoparticle concentration has not been tested in other studies; however, the combined findings of the current study align with those of previous studies, which documented an increase of flexural strength with low concentrations of NPs and low printing layer thicknesses separately (Reymus et al., 2019, Liu et al., 2021, Gad et al., 2022b, Zeidan et al., 2023, Farkas et al., 2023).

We also observed this combined effect in low printing layer thicknesses of 50 μm and 75 μm in which the addition of SiO_2NPs significantly increased the flexural strength. However, SiO_2NPs had no effect, regardless of the percentage added, when the layer thickness was increased to 100 μm. This verifies that the printing layer thickness has a greater impact than the addition of SiO_2NPs. According to our findings, a thin printing layer thickness combined with the addition of low concentrations of SiO_2NPs to 3D-printed resins can be recommended to significantly increase flexural strength and reduce their limited clinical use. However, the results of the current investigation must be fully understood before these parameters are implemented in the fabrication process of denture bases; therefore, future studies must combine the testing of other factors, such as printing direction and post-printing conditions, with low concentrations of SiO_2NPs and thin printing layer thickness.

This study had several limitations. First, only one printing direction was used. Second, the samples did not simulate denture configuration. Finally, only one type of metal oxide nanoparticle was used. Future recommendations include testing 3D-printed denture base resins with designed base configurations and teeth for other mechanical properties after they are modified with different metal oxide nanoparticles, printed in different printing directions, constructed in a denture shape, and exposed to combined thermomechanical stresses that can better mimic the oral environment.

5. Conclusions

The thickness of the printing layer affected the strength of the tested 3D-printed resins, and 100 μm LT decreased the flexural strength values significantly; however, all flexural strength values were above the ISO recommendations. SiO_2NP addition increased the flexural strength values of the 3D-printed resins. Therefore, the findings of the present study recommend low printing layer thicknesses with SiO_2NP addition for 3D-printed denture base fabrications.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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