

Wear resistance analysis of additively manufactured nanocomposite structures

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Numerous scientific studies describe the benefits of additive manufacturing for the purposes of prosthetic dental medicine. The materials used in this technology must have mechanical properties close to those of the tissues they aim to restore. The present study aims to test, under laboratory conditions, the wear resistance of additively manufactured trial nanocomposite specimens made from CROWNTEC. The specimens were grouped according to their orientation during printing. The surface normal vector in Group A forms an angle of 0° with the printing platform, in Group B – 30°, in Group C – 60°, and in Group D – 90°. To conduct the laboratory study, the "Sofia" chewing simulator was used. Spheres made of silicon nitride were selected as antagonistic elements, and distilled water was used as the liquid medium. Each specimen underwent 50,000 chewing simulation cycles, and the results were recorded using a Mettler Toledo ME303 analytical balance. After analyzing the results, it was found that the specimens had the highest average weight in Group B (6.526 g ± 0.037 g) and the lowest in Group D (6.511 g ± 0.032 g). The other two groups had an average weight of 6.515 g (±0.032 g) for Group C and 6.515 g (±0.044 g) for Group A. Wear of the material was greatest when the printed layers were at a 30° angle to the printing platform surface and lowest when the layers were parallel to the platform.

Keywords: additive manufacturing; wear resistance; nanocomposite materials; prosthetic dental medicine.

INTRODUCTION

Additive manufacturing is becoming increasingly applicable in all fields of dental medicine [1-4]. This technology enables the fabrication of 3D models through the layer-by-layer deposition of material [5-7]. Over the past decade, three-dimensional printing has become an alternative to subtractive manufacturing [8-10].

A primary priority in the treatment with removable and fixed prosthetic structures is the fulfillment of the medico-biological indicator "function," contributing to the long-term health of the patient [11-14]. 3D printing technology allows the use of various materials, facilitating the choice of this method for the fabrication of both removable and fixed prosthetic constructions [15-17]. Three-dimensional printing enables the rapid production of complex structures, significantly shortening the timeframes for therapeutic procedures [18].

The main requirements for materials used in fixed prosthetics are reviewed and summarized in numerous studies [3, 16, 19-21]. The mechanical and physical properties of both conventional and additive manufacturing materials should be close or

even identical to those of the tissues they replace [22-27].

One mechanical property of dental materials that attracts significant scientific interest is wear resistance [28-31]. Wear resistance is the property of a material to resist the process of abrasion. The chewing function is a mechanical loading process where restorative materials interact with opposing teeth, creating friction that results in the loss of both the material and the hard-dental tissues [19]. Wear depends on many factors, such as surface condition, structure homogeneity, material fatigue, load level, and the presence of intermediaries like saliva and food [20, 32-34].

The wear resistance of dental materials is critical to the clinical longevity of prosthetic structures. Abrasion of restorative materials deteriorates aesthetics and promotes the adhesion of microorganisms to prosthetic surfaces [35].

Ceramic materials and metal alloys are preferred for permanent fixed structures due to their low wear rates, whereas resin-based materials exhibit significantly higher abrasion [23, 36-38]. The growing interest in additive manufacturing requires the development of new generations of materials

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suited for this technology. To meet the needs of fixed prosthetics, composites reinforced with inorganic fillers such as zirconium nanoparticles, silanized dental glass, and ceramics are now being introduced to the market [39].

In 2022, SAREMCO (Switzerland) introduced a new nanocomposite material with ceramic inclusions for additive manufacturing of permanent fixed restorations – CROWNTEC. The material is designed for the fabrication of permanent restorations, such as single crowns, inlays, onlays, and veneers. Composition-wise, it is a light-curing, flowable methacrylic acid-based polymer [40, 41]. Due to its composition and the relevance of additive technologies, this new generation of materials is a justified subject of scientific interest.

The mechanical characteristics of resin-based materials depend on several factors, such as filler shape, filler size, hardness, and printing parameters [39, 42]. Studies have shown that these materials are susceptible to rapid aging. When exposed to liquid environments like the oral cavity, resin-based materials absorb water, leading to a degradation of their mechanical properties by affecting the polymer network [43].

The available scientific literature indicates that additive manufacturing offers the possibility to produce fixed prosthetic structures using modern nanocomposites [18, 44]. The wear resistance of these materials determines their clinical longevity and functionality [39]. The mechanical characteristics of resinous structures applied *via* 3D printers highlight the necessity for laboratory studies in this area. Analyzing wear resistance is crucial to determining their potential for use in fixed prosthetics [8, 19].

AIM OF THE STUDY

The present study aims to laboratory test the wear resistance of additively manufactured trial nanocomposite bodies made from CROWNTEC material.

Null Hypothesis (H_0): The weights of the specimens are comparable across all groups.

Alternative Hypothesis (H_1): The weights of the specimens vary significantly among the groups.

MATERIALS AND METHODS

For the study, 60 trial bodies were manufactured from the nanocomposite material CROWNTEC (SAREMCO, Switzerland) with incorporated ceramics. The specimens were divided into four groups based on their spatial orientation during printing:

Group A: normal vector forms an angle of 0° with the printing platform surface;

Group B: normal vector forms an angle of 30° with the printing platform surface;

Group C: normal vector forms an angle of 60° with the printing platform surface;

Group D: normal vector forms an angle of 90° with the printing platform surface.

The difference in spatial orientation during additive manufacturing leads to structural differences corresponding to the angles of 0° , 30° , 60° , and 90° .

The digital design and preparation for printing were carried out using the "3D Sprint" software, while the specimens were printed using a NextDent 5100 (NextDent, USA) 3D printer based on digital light processing (DLP).

Laboratory tests were performed using the "Sofia" chewing simulator, developed by Dr. I. Chakalov [45]. Specimens were cylindrical, with an external diameter of 25 mm and a height of 9 mm, as per the simulator requirements. Silicon nitride (Si_3N_4) spheres were used as antagonists (Fig. 1), and distilled water was the liquid medium.



Figure 1. Silicon nitride spheres.

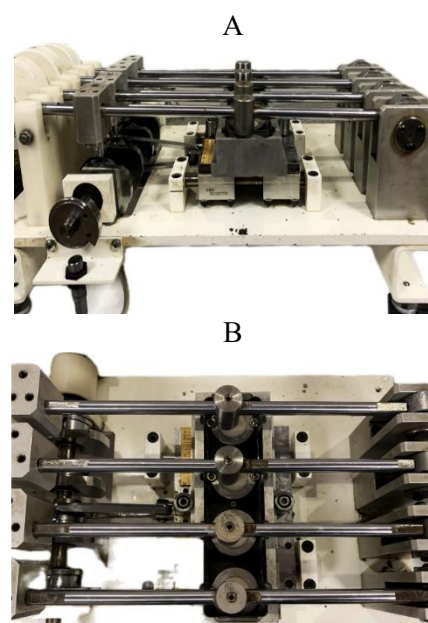


Figure 2. Chewing simulator "Sofia".

The testing methodology consisted of the antagonist descending onto the sample to simulate initial tooth contact, followed by a sliding movement with dynamic force variation, ending with the antagonist detaching from the sample. Each specimen underwent six paths, equating to 50,000 chewing cycles (Fig. 2 A and B).

Measurements were taken using the Mettler Toledo ME303 (Mettler Toledo, Switzerland) analytical balance to determine the sample masses before and after the chewing simulation (Fig. 3 A and B).

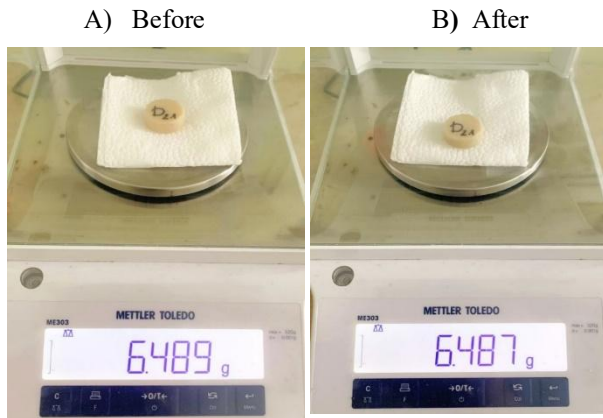


Figure 3. Mettler Toledo ME303 analytical balance measuring sample weights before and after the simulation.

Statistical methods used

- Descriptive statistics
 - Average – a measurement of the average tendency;
 - Mean – a measurement of the characteristic in the middle;
 - Standard deviation (SD) – a measurement of the average dispersion;
 - Lower (LCL) and Upper (UCL) – the limits within which the actual mean of the general population lies;
 - Absolute (N) values – a measurement for determining the number of cases;
 - Minimum value and Maximum value.
- Hypothesis testing
 - Parametric test for difference in "k" number of independent samples (ANOVA test);

- Post-hoc test to determine between which groups of "k" number of independent samples are significant differences;
- The independent samples t-test (also known as the two-sample t-test) is a parametric statistical test used to determine whether there is a significant difference between the means of two independent groups.

All hypothesis testing was conducted with a 5% significance threshold.

Statistics were performed with IBM SPSS Statistics 26, and graphs were generated with Excel 2010.

RESULTS

In the present study, a total of 60 test specimens were examined, evenly distributed into four groups (A, B, C, and D) according to the angle of the normal vector to the surface relative to the printing platform (angles of 0°, 30°, 60°, and 90°, respectively). The mass of the specimens was measured in grams both before and after the experiment in order to assess the level of wear resistance.

The measured average mass of the specimens prior to the experiment was 6.535 g, with a standard deviation of ± 0.039 g. The lightest specimen weighed 6.460 g, while the heaviest weighed 6.612 g. Half of the specimens were lighter than 6.534 g, and the other half were heavier.

The measured average mass of the specimens after the experiment was 6.517 g, with a standard deviation of ± 0.036 g. The lightest specimen weighed 6.449 g, and the heaviest weighed 6.579 g. Half of the specimens were lighter than 6.519 g, and the other half were heavier. (Table 1). When examining the differences between the mean weights of the specimens in the groups at the beginning of the experiment, the highest mean weight was recorded in Group B (6.563 g ± 0.036 g), while the lowest mean weight was observed in Group D (6.517 g ± 0.031 g). The remaining two groups had mean weights of 6.528 g (± 0.033 g) for Group C and 6.530 g (± 0.041 g) for Group A. The difference between the groups is graphically represented in Figure 4.

Table 1. Summary of the statistical characteristics of the sample. Unit of measurement: (g)

Group	Mean	Median	Std. deviation	Minimum	Maximum	LCL/UCL	N
Before the experiment	6.535	6.534	0.039	6.460	6.612	6.525 / 6.544	60
After the experiment	6.517	6.519	0.036	6.449	6.579	6.499 / 6.535	60

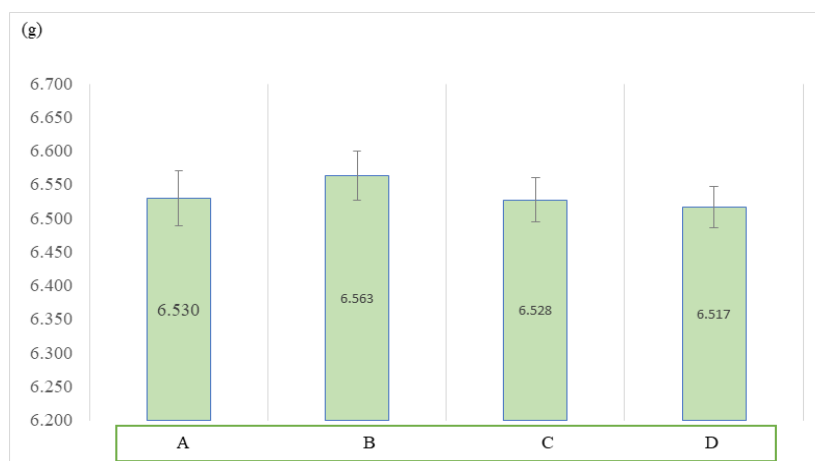


Figure 4. Difference in the weights of the specimens between groups at the beginning of the experiment, (g).

The significance level was determined with a test error of 5%. The distribution of weights was assessed using the Kolmogorov-Smirnov test, which confirmed a normal distribution of weights within each group (Table 2). Therefore, the differences were analyzed using analysis of variance (ANOVA) for comparing the means of several independent samples.

Table 2. Results of the normality test for the weight distribution within each group prior to the experiment. One-Sample Kolmogorov-Smirnov Test

Group		Weight before (g)	Result
A	Asymp. Sig. (2-tailed)	.200 ^{a, b}	Normal distribution
B	Asymp. Sig. (2-tailed)	.054 ^a	Normal distribution
C	Asymp. Sig. (2-tailed)	.200 ^{a, b}	Normal distribution
D	Asymp. Sig. (2-tailed)	.200 ^{a, b}	Normal distribution

^a Lilliefors significance correction. ^b This is a lower bound of the true significance.

The significance level obtained from the test [$p = 0.5\%$] is lower than the accepted risk of error of 5%. Therefore, the alternative hypothesis is accepted, stating that there is a statistically significant difference in the weights of the specimens between

the groups prior to the experiment. To determine specifically between which groups the differences are significant, a post-hoc test was conducted using the Least Significant Difference (LSD) test. The results revealed that a significant difference exists between the weight of Group B and the weights of all other groups, while no significant differences were found among Groups A, C, and D. This conclusion can be stated with 95% confidence (Table 3).

Following the statistical analysis of the data regarding differences in mean weights between groups after the experiment, the highest mean weight was observed in Group B (6.526 g $\pm$ 0.037 g), while the lowest mean weight was found in Group D (6.511 g $\pm$ 0.032 g). The other two groups exhibited mean weights of 6.515 g ($\pm$ 0.032 g) for Group C and 6.515 g ($\pm$ 0.044 g) for Group A. The differences between the groups are graphically presented in Figure 5.

Testing the weight distribution after the experiment using the Kolmogorov-Smirnov test indicated a normal distribution within each group (Table 4). Therefore, the verification of differences was conducted through analysis of variance (ANOVA) for comparing the means of several independent samples.

Table 3. Results from the test of differences in specimen weights between groups prior to the experiment.

Char. under test	Tested group	Characteristics	Groups under test			
			A	B	C	D
Weight		Mean	6.530 ^A	6.563 ^B	6.528 ^A	6.517 ^A
		SD	± 0.041	± 0.036	± 0.033	± 0.031
		N	15	15	15	15
ANOVA test		P-value	$p = 0.005$			

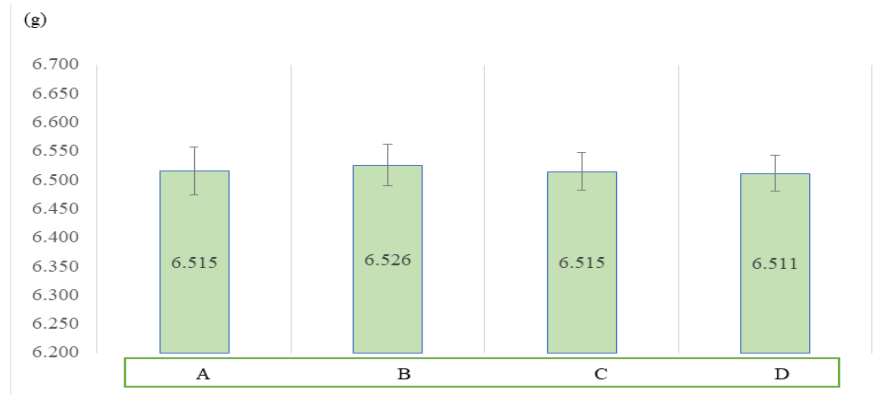


Figure 5. Differences in specimen weights between groups after completion of the experiment, (g).

Table 4. Results of the normality test for the distribution of specimen weights within each group after the experiment. One-Sample Kolmogorov-Smirnov Test

Group		Weight before (g)	Result
A	Asymp. Sig. (2-tailed)	.200 ^{a, b}	Normal distribution
B	Asymp. Sig. (2-tailed)	.071 ^a	Normal distribution
C	Asymp. Sig. (2-tailed)	.200 ^{a, b}	Normal distribution
D	Asymp. Sig. (2-tailed)	.200 ^{a, b}	Normal distribution

^a Lilliefors significance correction. ^b This is a lower bound of the true significance.

The significance level obtained from the test [$p = 74.1\%$] is higher than the accepted risk of error of 5%. Therefore, the null hypothesis is accepted, stating that there is no statistically significant difference in the weights of the specimens between the groups, and that any observed differences are of a random nature. This indicates that the wear resistance across the groups after the experiment is identical. This conclusion can be stated with 95% confidence (Table 5).

Additionally, the difference between the mean weights of the specimens in the groups before and after the experiment was determined. The greatest

difference in weight after the experiment was observed in Group B, where, as a result of wear resistance, a decrease of -0.038 g was recorded. The smallest difference in weight after the experiment was observed in Group D, with a decrease of -0.006 g due to wear resistance. In the remaining two groups, the decreases in weight were -0.015 g for Group A and -0.013 g for Group C. Graphically, the differences among the groups are presented in Figure 6.

The distribution of the weights within the groups had already been tested using the Kolmogorov–Smirnov test (Tables 2 and 4), which indicated a normal distribution of weights in each group. Therefore, the verification was performed using a T-test for the difference between two means of two related samples.

The significance level obtained from the tests [$p < 0.001\%$] is lower than the accepted risk of error of 5%. Consequently, the alternative hypothesis is accepted, stating that there is a statistically significant difference in the direction of weight reduction after the experiment. This indicates that statistically significant wear occurred in each group. This conclusion can be stated with 95% confidence (Table 6).

Table 5. Results from the test of differences in specimen weights between groups after the experiment.

Char. under test \ Tested group	Characteristics	Groups under test			
		A	B	C	D
Weight	Mean	6.515 ^A	6.526 ^A	6.515 ^A	6.511 ^A
	SD	±0.044	±0.037	±0.032	±0.032
	N	15	15	15	15
ANOVA test	P-value	p=0.741			

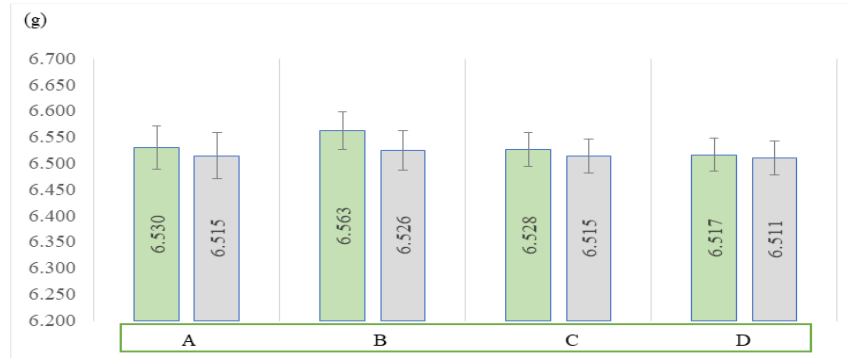


Figure 6. Difference in specimen weights in the groups before and after the experiment, (g).

Table 6. Results from the test of differences in specimen weights between groups prior to the experiment.

Tested group Char. under test	Characteristics	Groups under test							
		A		B		C		D	
		Before	After	Before	After	Before	After	Before	After
Weight	Mean	6.530 ^A	6.515 ^B	6.563 ^A	6.526 ^B	6.528 ^A	6.515 ^B	6.517 ^A	6.511 ^B
	SD	±0.041	±0.044	±0.036	±0.037	±0.033	±0.032	±0.031	±0.032
	N	15	15	15	15	15	15	15	15
T test	P-value	p<0.001		p<0.001		p<0.001		p<0.001	

DISCUSSION

The results of the conducted study confirmed the null hypothesis when comparing the mass between the groups before and after the experiment.

Analysis of the specimens' mass before and after the chewing simulation suggests a probable dependence on the orientation during the printing process.

Prior to the laboratory testing, the mean mass of the specimens in Group B was the highest (6.563 g ±0.036 g), while Group D exhibited the lowest mean mass (6.517 g ±0.031 g). Groups A and C demonstrated intermediate values with relatively close mean weights (6.530 g and 6.528 g, respectively), suggesting a potential influence of the printing angle on the specimens' mass, possibly due to differences in layer structure and degree of compaction.

Following the application of the laboratory chewing simulation, the same trend in the distribution of group weights was observed. Group B again showed the highest mean weight (6.526 g ±0.037 g), and Group D remained the lowest (6.511 g ±0.032 g). Groups C and A continued to exhibit closely aligned values (6.515 g), highlighting that the initial differences in specimen mass persisted after simulation without leading to significant changes in the dynamics between the groups.

The differences between the groups after loading were minimal, indicating that regardless of the initial mass, the specimens exhibited relatively similar behavior in terms of wear resistance. This, in turn,

suggests that spatial orientation affects the initial parameters of the specimens but does not have a substantial impact on wear resistance during chewing simulation.

When comparing the differences in the mean mass of the specimens within the groups before and after the experiment, a statistically significant difference was identified, leading to the rejection of the null hypothesis and confirmation of the alternative hypothesis.

Analysis of the results from the laboratory investigation showed that the greatest average weight loss occurred in Group B, where the post-experimental weight difference was 0.038 g, and the smallest in Group D – 0.006 g. For the other two groups (A and C), the average material loss was 0.015 g and 0.013 g, respectively.

These values highlight the existence of a relationship between the spatial orientation of the material layers on the studied surface of the specimens and wear resistance. Specimens from Group B, where the normal vector to the surface forms a 30° angle with the printing platform, demonstrated the highest susceptibility to material loss under mechanical loading, likely due to the specific arrangement of layers during printing. This could lead to lower structural stability of constructions in the long term.

The specimens from Group D, where the normal vector to the surface forms a 90° angle, exhibited the lowest degree of wear. This may indicate better wear resistance of the material when the structural layers

are horizontally oriented relative to the printing platform.

The discussed results support the hypothesis that the spatial orientation of the specimens during printing influences the material's wear resistance. These findings could serve as a foundation for determining the optimal orientation in the design and printing of structures made from the nanocomposite material CROWNTEC. Proper spatial orientation of the material layers in permanent fixed constructions could contribute to the long-term success of prosthetic treatment.

CONCLUSIONS

In conclusion, the results of the present study clearly highlight the significant influence of the structural orientation of the layers in additively manufactured specimens made of the nanocomposite material CROWNTEC on the wear resistance of their surfaces. Furthermore, the scientific investigation demonstrated that the printing angle affects the mass of the printed objects.

The highest degree of wear occurred when the material layers were oriented at a 30° angle, while the lowest wear was observed when the layers were horizontally oriented relative to the printing platform, where the normal vector to the surface forms a 90° angle. This leads to the conclusion that the specimens from Group D possess the highest wear resistance.

The results of the present study are supported by findings in a scientific paper published in 2022 [46], where the CROWNTEC material demonstrated relatively low wear values ($35.5 \pm 30.2 \mu\text{m}$). This aligns with the hypothesis that both the material composition and the spatial orientation during 3D printing play a crucial role in determining wear resistance.

Conversely, in a more recent study by Grymak et al. (2024) [47], CROWNTEC exhibited a higher tendency to wear compared to other additively manufactured materials, such as NextDent C&B MFH, particularly under varying loads and environmental conditions. The authors highlight the importance of surface treatment in enhancing wear resistance, suggesting that a combination of optimal spatial orientation and proper surface finishing may significantly improve the performance of prosthetic structures made from CROWNTEC.

Additionally, a comparative study by Türksayar et al. (2024) [48] reinforced the significance of spatial orientation in additive manufacturing by evaluating the mechanical properties of 3D printed versus subtractively manufactured implant-supported crowns. Their findings show that

additively manufactured crowns may possess competitive, or even superior, wear resistance under specific conditions. These results further support the hypothesis that well-defined printing parameters are essential in optimizing the long-term durability of prosthetic constructions made from CROWNTEC.

The experimental data suggests that, for practical applications, it is advisable to orient the material layers' parallel to the printing platform in the zones subject to mechanical loading, in order to enhance the wear resistance of permanent fixed constructions.

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