ORIGINAL ARTICLE
DOI: 10.5152/EssentDent.2026.25073

Investigation of Changes in Surface and Optical Properties of 3D-Printed Acrylic Resins Produced with Different Layer Thickness and Curing Methods: An In Vitro Study

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Cite this article as: Öztürk Z, Tosun B. Investigation of changes in surface and optical properties of 3D-printed acrylic resins produced with different layer thickness and curing methods: an in vitro study. *Essent Dent.* 2026, 5, 0073, doi:10.5152/EssentDent.2026.25073.

Abstract

Background: This in vitro study aimed to evaluate the effects of different layer thicknesses (50 μm and 100 μm) and curing methods (light curing and water curing) on the surface roughness, microhardness, and color stability of 3D-printed Polymethyl Methacrylate (PMMA) based denture base resins after exposure to 2 acidic aging solutions—cola and sour cherry juice.

Methods: One hundred twenty disc-shaped samples were 3D-printed and divided into 4 main groups based on layer thickness and curing method. Each group (n = 30) was further divided into subgroups (n = 15) and immersed in either cola or sour cherry juice for 7 and 21 days. Surface roughness, Vickers microhardness, and color change (ΔE) were measured each time. Statistical analyses included repeated measures ANOVA, Friedman, and Wilcoxon tests ($P < .05$).

Results: Surface roughness values significantly increased over time in all groups ($P < .05$); however, no significant difference was detected between the groups at any time point. Microhardness values showed significant differences according to layer thickness, curing method, and time ($P < .05$). While higher hardness values were obtained in 50 μm and light-cured groups, a significant decrease was observed in all groups over time. A statistically significant ΔE was observed in the 50 water-cured–cola group, while color stability was maintained in the other groups.

Conclusion: Layer thickness, curing method, and aging process have a significant impact on the surface and optical properties of 3D-printed PMMA resins. Water curing may limit polymerization efficiency, resulting in increased susceptibility to surface degradation and color changes. Optimizing manufacturing parameters is crucial for enhancing the clinical performance and long-term aesthetics of 3D-printed prosthetic materials.

Keywords: 3D printing, acrylic resins, surface properties

What is already known on this topic?

- *Layer thickness and curing method have decisive effects on the surface roughness, microhardness, and optical properties of 3D-printed PMMA-based dental materials.*
- *Thinner layer thickness and light-curing method generally improve the initial optical and mechanical properties of these materials.*
- *However, there is limited data in the literature on the post-aging performance of these materials, i.e., how they respond to the conditions that may be encountered during clinical use.*

What this study adds on this topic?

- *This study revealed the changes in surface roughness, microhardness, and color stability of 3D-printed PMMA-based materials by evaluating the parameters such as layer thickness, curing method, and aging solution together.*
- *Significant changes were observed in optical and surface properties after aging, especially in samples produced with thin layers and applied with water curing.*
- *The obtained data contribute to a better understanding of the effect of production parameters on long-term clinical performance.*

INTRODUCTION

Today, with the advancement of technological possibilities, three-dimensional (3D) measurement and intraoral scanning, computer-aided personalized design applications, digital appliances, and prostheses prepared through 3D modeling systems are becoming increasingly integrated into routine clinical practices.[1]

Three-dimensional printing technology, also known as additive manufacturing, enables the creation of 3D objects by combining various materials such as plastic, metal,

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Received: June 12, 2025
Revision requested: August 11, 2025
Last revision received: August 14, 2025
Accepted: October 13, 2025
Publication Date: March 4, 2026

ceramic, and living cells in successive layers.[2] Liquid resins are deposited sequentially in layers and subsequently solidified through the application of heat and light.[3] This technology enables less invasive and high-precision applications, thereby reducing patient chairside time. It also increases patient comfort and minimizes psychological trauma caused by multi-stage treatment processes, offering remarkable advantages in pediatric applications.[4] Especially in the rehabilitation processes of anxious children or those with special needs, digitally produced 3D-printed prostheses are essential in reducing the stress caused by traditional methods.[4,5] In addition, this technology, which is effectively used in producing fixed and mobile appliances and space maintainers, provides superior compatibility and high precision by minimizing human error in the production process.[6]

Printing parameters, such as printing direction and layer thickness, affect properties including printing accuracy, mechanical strength, surface properties, and microbial adhesion of restorative materials obtained through 3D printing technology.[7,8] Layer thickness is a critical parameter in the 3D printing process that directly influences the quality of the printed object. However, the optimal value for this parameter, which dictates the thickness of each printed layer, remains unclear in the existing literature. Although specific studies suggest that using thinner layers enhances mechanical strength and surface smoothness, other research has reported no notable differences in mechanical properties across varying layer thicknesses.[9-11] However, the curing protocols applied in the final processing stage (curing with light, heat, or in water) also directly affect the mechanical and surface properties of the material by increasing the degree of polymerization.[12-14] The effect of these parameters on the material's physical properties and color stability is of great importance for the clinical success of restorations.[15] Although studies are addressing the effects of manufacturing and finishing parameters on the physical and optical changes produced by 3D printing,[16-18] examples addressing denture base materials are pretty limited.[19,20] This in vitro study aims to evaluate the effects of 3D-printed acrylic resins produced with different layer thicknesses and curing methods on surface roughness, microhardness, and color stability properties after exposure to aging solutions. The null hypothesis of this study was that differences in layer thickness and curing method would not cause significant changes in the surface and optical properties of 3D-printed acrylic resin samples after exposure to coloring agents.

MATERIALS AND METHODS

A priori power analysis (G*Power version 3.1.9.7, Heinrich Heine University Düsseldorf, Düsseldorf, Germany) was conducted to determine the appropriate sample size. It was shown that at least 104 specimens were required for the highest power level (power=0.80, effect size of 0.40, α=0.05). To ensure adequate sample size and account for potential specimen loss, 2 additional specimens were prepared for each group, resulting in a total of 120 specimens (n=15 per subgroup).

One hundred twenty disc-shaped samples of 8 × 2 mm dimensions were produced by 3D printing to evaluate surface roughness, microhardness, and color change. Half of the samples were fabricated with a 50 μm layer thickness, while the remaining half were produced using a 100 μm layer thickness; light curing was applied to half of each layer thickness group, and water curing was applied to the other half (n=30 in each group). The 4 main groups were divided into 2 subgroups for evaluation in 2 aging solutions (n=15).

Since this study is an in vitro investigation that does not involve human participants, neither ethical approval nor informed consent was required.

Specimen Design and Preparation

A PMMA-based denture base resin designed for 3D printing (PowerResins Denture Resin, 3BFAB Technology Inc., Istanbul, Türkiye) was utilized in this study. Sample models were created using Meshmixer software (Autodesk Inc.) and exported to the printer's slicing software. The samples were fabricated with a DentaFab Sega 3D printer (DentaFab, Istanbul, Türkiye). During printing, parameters such as support type and printing angle were kept constant, and only the layer thickness was changed at 2 different levels, 50 μm and 100 μm.

Following the printing process, the samples were cleaned according to the manufacturer's guidelines. The cleaning process was carried out in the first chamber, which contained 96% ethanol (MediFive Twin Cure, South Korea), for 3 minutes. The sample was then dried using an air spray. The procedure was repeated in the second chamber, with particular attention given to keeping the total cleaning duration within 6 minutes.

After washing, half of the samples were polymerized for 30 minutes in a device emitting Ultraviolet (UV) light in the 365-405 nm wavelength range (MediFive Twin Cure). The other half was cured for 5 minutes under 405 nm light in a water-protected curing unit (Nova3D Fastcure, Shenzhen Nova Intelligent Technology, China), in accordance with the manufacturer's instructions and consistent with protocols reported in previous studies.[11] After the printing supports were carefully removed, all samples were surface treated by the same operator in a water-cooled environment at 300 rpm using 600, 800, 1000, and 1200 grit silicon carbide sandpapers, respectively. The prepared samples were kept in a distilled water bath at 37°C for 24 hours and then dried with a paper towel. The thickness measurements were verified with a digital caliper (Digimatic AOS, Mitutoyo A.G., Japan). The detailed classification of the study groups is presented in Table 1.

Table 1. Classification of the Study Groups According to Layer Thickness, Curing Method, and Aging Solution

	Layer Thickness	Curing Method	Aging Solution
Material (PowerResins Denture Resin)	50 µm	MediFive Twin Cure (Light-cured)	Sour cherry juice (50-LC-Ch)
			Cola (50-LC-C)
		Nova 3D Fastcure (Water-cured)	Sour cherry juice (50-WC-Ch)
			Cola (50-WC-C)
	100 µm	MediFive Twin Cure (Light-cured)	Sour cherry juice (100-LC-Ch)
			Cola (100-LC-C)
		Nova 3D Fastcure (Water-cured)	Sour cherry juice (100-WC-Ch)
			Cola (100-WC-C)

C, Cola; Ch, sour cherry juice; LC, light-cured; WC, water-cured.

Aging Procedure

The aging procedure was performed by dividing the specimens into 2 groups according to the aging solution used: sour cherry juice (Dimes Sour Cherry Juice, Türkiye; pH 3.24 ± 0.01) and cola (Coca-Cola, The Coca-Cola Company, USA; pH 2.37 ± 0.01) were used as aging solutions. The pH values of each solution were measured at room temperature using a calibrated digital pH meter (Ohaus ST3100-F, USA). All samples from each group were immersed in 10 mL of their respective solution for 10 minutes daily for 21 consecutive days to simulate beverage ingestion. During the remainder of each day, the samples were rinsed with distilled water and stored in fresh distilled water at 37°C until the next cycle.[21] These beverages were selected due to their acidic nature and widespread consumption, particularly among pediatric patients, as acidic drinks have been shown to adversely affect the surface and optical properties of denture base resins and acrylic materials.[21,22] All solutions were renewed daily. Surface roughness, microhardness, and color measurements were performed at baseline, after 7 days, and after 21 days of immersion.

Surface Roughness Measurements

Surface roughness assessments were performed using a portable profilometer (Mahr, Marsurf M400, Germany). Before starting the measurements, the device was calibrated with a standard reference sample. Surface roughness (Ra) of each sample was determined in micrometers by averaging 3 individual measurements obtained from the center of the sample. Measurements were made using a scan length of 4 mm and a cut-off value of 0.8 mm after the samples were removed from the aging solutions on the 7th and 21st days.

Vickers Hardness Measurements

Surface microhardness of 8 × 2 mm samples was evaluated with a Vickers hardness tester (Shimadzu HMV-G, Japan). Tests were performed under a 50-g load and a 30-second application time. Measurements were taken from 3 different points on each sample, at least 1 mm apart, and the average of these measurements was reported as the Vickers hardness number. All hardness measurements were repeated on the 7th and 21st days.

Color Evaluation

The L* (lightness: 0 = black, 100 = white), a* (−a* = green, +a* = red), and b* (−b* = blue, +b* = yellow) coordinates of each specimen were recorded on a neutral gray background using a spectrophotometer (VITA Easyshade V, VITA Zahnfabrik, Germany) before immersion. The device was calibrated with its own calibration plate before each measurement session. For each specimen, 3 consecutive measurements were performed at the center, and the mean value was recorded for analysis. Following storage in the respective aging solutions for the predetermined periods, the specimens were rinsed thoroughly with distilled water, and color measurements were repeated on the 7th and 21st days. The color change (ΔE*ab) between baseline and each evaluation period was calculated using the formula:

$$\Delta E = [(L2 - L1)^{2} + (a2 - a1)^{2} + (b2 - b1)\ 2]^{½}$$

Statistical Analysis

Data were analyzed using Minitab v14 (Minitab Inc.) and Jamovi v2.3.28 (The Jamovi Project, Sydney, Australia) programs. Compliance with normal distribution was assessed using the Shapiro–Wilk test; the Friedman test was used for 3 or more dependent groups that did not have a normal distribution, the Wilcoxon test was used for comparisons of 2 dependent groups, and the paired two-sample *t*-test and repeated measures ANOVA were used for comparisons of normally distributed groups. In multifactorial analyses, main effects and interactions of layer thickness, curing method, solution, and time factors were evaluated using ANOVA. The significance level was accepted as $P < .05$; data were presented as mean ± SD or median (minimum-maximum).

RESULTS

In all groups, statistically significant increases were observed in surface roughness (Ra) values as time progressed ($P < .05$) (Table 2). In samples produced with a layer thickness of 50 µm and cured in aqueous medium, roughness values increased in both cola and sour cherry solutions ($P < .001$). Surface roughness also increased in groups produced with a layer thickness of 100 µm over time. In the aqueous cured cola group, average values rose from 0.670 to 0.820, and in the sour cherry group from 0.659 to 0.748 ($P < .001$ and $P = .002$).

As a result of microhardness measurements, statistically significant differences were observed in layer thickness, curing

Table 2. Time-Dependent Changes in Surface Roughness Between Groups

	Initial	Day 7	Day 21	Test Statistic	*P*
50-WC-C	0.548 (0.406-0.655)[a]	0.579 (0.506-0.919)[b]	0.658 (0.507-0.963)[c]	26.000	**<.001**[y]
50-WC-Ch	0.538 ± 0.066[a]	0.589 ± 0.073[b]	0.641 ± 0.097[c]	23.161	**<.001**[x]
50-LC-C	0.547 ± 0.043[a]	0.571 ± 0.049[b]	0.643 ± 0.087[c]	17.817	**<.001**[x]
50-LC-Ch	0.499 (0.456-0.582)[a]	0.571 (0.475-0.831)[b]	0.700 (0.613-0.873)[c]	26.000	**<.001**[y]
100-WC-C	0.670 ± 0.066[a]	0.733 ± 0.078[b]	0.820 ± 0.105[c]	22.636	**<.001**[x]
100-WC-Ch	0.659 ± 0.058[a]	0.696 ± 0.046[b]	0.748 ± 0.063[c]	12.680	**.002**[x]
100-LC-C	0.505 ± 0.046[a]	0.538 ± 0.049[b]	0.633 ± 0.079[c]	22.984	**<.001**[x]
100-LC-Ch	0.502 (0.419-0.704)[a]	0.538 (0.485-0.707)[b]	0.617 (0.499-0.893)[c]	26.000	**<.001**[y]

Mean ± SD, Median (Minimum-Maximum).Values in bold indicate statistically significant differences ($P < .05$).
C, Cola; Ch, sour cherry juice; LC, light-cured; WC, water-cured.
[a-c]No significant difference between groups sharing the same letter.
[x]Repeated measures ANOVA.
[y]Friedman test.

method, time, and several 2-way interactions (Tables 3 and 4). When evaluated according to layer thickness, the average microhardness value of the 50 μm group was 19.545. In comparison, this value was determined to be 18.958 in the 100 μm group, and the difference was statistically significant ($P = .024$). In contrast to the curing method, the average microhardness value was 18.831 for the samples cured with the water method and 19.672 for the samples cured with the light method. This difference was found to be significant ($P = .001$). A substantial decrease in microhardness values was observed as the time increased. While the average microhardness was 21.934 at the beginning, this value decreased to 18.840 on the 7th day and 16.980 on the 21st day ($P < .001$).

In addition, the interaction between the curing method and the solution was significant ($P = .029$); lower average microhardness values were observed, especially in the groups subjected to water curing and those exposed to cola solution. However, a significant difference was also found in the interaction between the curing method and time ($P = .001$); the highest hardness values were observed at the beginning in both curing methods, while the lowest values were recorded on day 21. Other main effects and interactions were not statistically significant ($P > .05$).

When evaluated regarding color change, a statistically significant difference between the first and second ΔE values was found only in samples produced with a layer thickness of 50 μm and exposed to the cola solution after aqueous curing ($P = .033$) (Table 5).

However, no statistically significant difference was found between the first and second ΔE values in all other groups ($P > .05$).

DISCUSSION

The physical and optical properties of PMMA-based dental materials produced by 3D printing vary significantly depending on the applied production parameters.[11,23] It has been reported in various studies that factors such as layer thickness and post-polymerization method can be decisive on mechanical resistance, surface morphology, and aesthetic performance.[17,19] Accordingly, this study aimed to evaluate the effects of different layer thickness and curing methods on the surface roughness, microhardness, and color stability of acrylic resins produced by 3D printing. The findings showed statistically significant differences between the groups, and the null hypothesis was rejected.

Surface roughness in acrylic dentures is a critical parameter that directly affects clinical success in both aesthetic and biological terms.[24,25] Previous studies have shown that rough surfaces increase the risk of oral infection by promoting microorganism accumulation and reducing the lifespan of the denture.[26,27] In addition, Li et al[28] observed that layer thicknesses exceeding 100 μm promoted the formation of Candida albicans biofilms, while thinner layers (below 100 μm) diminished microbial adhesion and enhanced aesthetic outcomes. Moreira et al[29] reported that the surface roughness was lower in 3D-printed samples produced with a thinner layer thickness (25 μm) and that this situation was maintained after aging. In the current study, although the highest roughness values were seen in samples subjected to 100 μm aqueous curing at all times, no significant difference was observed in the initial surface roughness values between the groups. Çakmak et al[30] reported no significant change was observed in the surface roughness of 3D-printed prosthesis base materials subjected to coffee thermal cycling. In contrast, this study detected substantial increases in surface roughness over time in all groups after chemical aging with low-pH beverages, such as cherry juice and cola. Applying different aging protocols stands out as a decisive factor in explaining the changes observed on the surface. Similarly, in the study conducted by Tosun et al,[20] it was reported that the surface roughness of 3D-printed PMMA materials, both heat polymerized and produced with different printing angles, increased significantly after chemical aging with commercial orange juice, and this increase was related to the effect of the acidic environment. This effect can be attributed to the fact that components such as phosphoric and citric acid in the solution content cause

Table 3. Time-Dependent Changes in Microhardness Between Groups

Time (Day)	Curing Method	Aging Solution	Layer Thickness 50 μm	Layer Thickness 100 μm	Total
Initial hardness	Water-cured	Cola	22.623 ± 3.459	20.871 ± 3.007	21.715 ± 3.292
		Sour cherry juice	22.615 ± 2.432	22.625 ± 2.162	22.62 ± 2.258
		Total	22.619 ± 2.929	21.681 ± 2.748	22.15 ± 2.852[A]
	Light-cured	Cola	22.862 ± 2.942	20.946 ± 2.311	21.904 ± 2.77
		Sour cherry juice	21.854 ± 2.415	21.208 ± 2.068	21.531 ± 2.227
		Total	22.358 ± 2.687	21.077 ± 2.153	21.717 ± 2.496[A]
	Total	Cola	22.742 ± 3.148	20.907 ± 2.643	21.808 ± 3.019
		Sour cherry juice	22.235 ± 2.406	21.888 ± 2.192	22.065 ± 2.287
		Total	22.489 ± 2.786	21.379 ± 2.463	21.934 ± 2.676[a]
Day 7 hardness	Water-cured	Cola	17.885 ± 1.863	16.314 ± 2.727	17.07 ± 2.441
		Sour cherry juice	19.362 ± 1.961	18.842 ± 1.621	19.112 ± 1.788
		Total	18.623 ± 2.019	17.481 ± 2.583	18.052 ± 2.367[C]
	Light-cured	Cola	19.839 ± 1.498	19.639 ± 2.083	19.739 ± 1.78
		Sour cherry juice	19.669 ± 1.801	19.369 ± 1.544	19.519 ± 1.65
		Total	19.754 ± 1.625	19.504 ± 1.802	19.629 ± 1.703[B]
	Total	Cola	18.862 ± 1.932	17.915 ± 2.93	18.379 ± 2.513
		Sour cherry juice	19.515 ± 1.851	19.116 ± 1.571	19.32 ± 1.714
		Total	19.189 ± 1.902	18.492 ± 2.43	18.84 ± 2.2[b]
Day 21 hardness	Water-cured	Cola	16.315 ± 1.83	16.529 ± 2.168	16.426 ± 1.977
		Sour cherry juice	15.585 ± 2.047	16.75 ± 2.066	16.144 ± 2.098
		Total	15.95 ± 1.939	16.631 ± 2.082	16.29 ± 2.021[D]
	Light-cured	Cola	17.754 ± 1.3	17.615 ± 2.229	17.685 ± 1.789
		Sour cherry juice	18.177 ± 1.555	17.131 ± 1.398	17.654 ± 1.544
		Total	17.965 ± 1.421	17.373 ± 1.839	17.669 ± 1.655[C]
	Total	Cola	17.035 ± 1.72	17.052 ± 2.225	17.043 ± 1.974
		Sour cherry juice	16.881 ± 2.218	16.948 ± 1.723	16.914 ± 1.971
		Total	16.958 ± 1.966	17.002 ± 1.981	16.98 ± 1.964[c]
Total	Water-cured	Cola	18.941 ± 3.648	17.905 ± 3.351	18.404 ± 3.514[B]
		Sour cherry juice	19.187 ± 3.588	19.406 ± 3.117	19.292 ± 3.35[AB]
		Total	19.064 ± 3.597	18.597 ± 3.311	18.831 ± 3.454
	Light-cured	Cola	20.151 ± 2.914	19.4 ± 2.56	19.776 ± 2.751[A]
		Sour cherry juice	19.9 ± 2.443	19.236 ± 2.361	19.568 ± 2.41[A]
		Total	20.026 ± 2.674	19.318 ± 2.448	19.672 ± 2.58
	Total	Cola	19.546 ± 3.336	18.625 ± 3.071	19.077 ± 3.227
		Sour cherry juice	19.544 ± 3.071	19.317 ± 2.732	19.433 ± 2.902
		Total	19.545 ± 3.196	18.958 ± 2.925	19.251 ± 3.072

[A-C]There is no difference between interactions with the same letter.
[a-c]There is no difference between groups with the same letter.

dissolution and softening of the polymer surface, disrupting surface integrity.[21]

Color stability in PMMA-based restorative materials is a key factor in determining the long-term aesthetic success of the restoration. Failure to achieve color stability may deteriorate esthetic harmony over time, and reconstruction may be needed.[31] Therefore, parameters such as curing methods, layer thickness, and environmental exposure conditions used in producing the material should be carefully considered. The ΔE values obtained in this study were compared with the widely accepted perceptibility (1.2) and acceptability (2.7) thresholds reported in the literature.[32] Most of the mean ΔE values measured on days 7 and 21 were above the perceptibility threshold but below the acceptability threshold, indicating that the color changes were generally perceivable but clinically acceptable. Lee et al[15] reported that under the same printing direction and aging time, groups with 100 μm layer thickness exhibited lower ΔE_{00} values compared to 25 μm groups. The layer thickness significantly affected the color stability of 3D-printed resins. It was also emphasized that color change did not always increase in proportion to the immersion time, and could differ depending on the chemical properties of the dye solution used. These findings are consistent with the conclusion that a statistically significant difference was found between ΔE values only in the

Table 4. Comparison of Microhardness Values According to Layer Thickness, Curing Method, Solution, and Time

	F	*P*	η^2
Layer thickness	5.128	**.024**	0.017
Curing method	10.851	**.001**	0.036
Solution	1.823	.178	0.006
Time	138.02	**<.001**	0.489
Layer thickness × Curing method	0.367	.545	0.001
Layer thickness × Solution	1.851	.175	0.006
Layer thickness × Time	1.766	.173	0.012
Curing method × Solution	4.807	**.029**	0.016
Curing method × Time	6.756	**.001**	0.045
Solution × Time	1.495	.226	0.010
Layer thickness × Curing method × Solution	1.401	.237	0.005
Layer thickness × Curing method × Time	1.491	.227	0.010
Layer thickness × Solution × Time	0.803	.449	0.006
Curing method × Solution × Time	2.077	.127	0.014
Layer thickness × Curing method × Solution × Time	0.16	.852	0.001

F, ANOVA test statistic; η^2, partial eta squared.
R^2 = 53.55%; Adjusted R^2 = 49.84%.

50-WC-C group in this study. At the same time, color stability was preserved mainly in the other groups. Similarly, in the study of Espinar et al,[16] in parallel with the current findings, it was reported that color change occurred at a lower level in samples produced with thicker layer thicknesses. In this context, it is thought that the lower color change values obtained with a layer thickness of 100 μm may be due to the limitation of the effect of external factors that may cause color change due to the formation of fewer layer interfaces.[16]

Lassila et al[31] reported that curing conditions can significantly affect mechanical properties, whereas changes in optical properties are more limited. Additionally, there is evidence that curing protocols, particularly those involving water, can weaken interchain bonding during the polymerization process, thereby negatively affecting color stability.[11] The significant color change observed when exposed to cola solution, especially in samples produced with a layer thickness of 50 μm and cured in aqueous media, suggests that this group may be more sensitive to acidic environments. The lower pH value of cola compared to cherry juice, combined with its phosphoric acid content, may be a factor that negatively affects color stability.

Microhardness is a crucial physical property for the functional durability and clinical performance of denture base materials.[33] In previous studies, it has been reported that samples produced with a thinner layer thickness have higher microhardness values.[11,34] These findings are consistent with the results of the present study, which were obtained before aging with sour cherry juice and cola content. Çakmak et al[30] reported that the layer thickness affects the microhardness of additively produced prosthesis base materials. Although higher hardness is initially achieved in thin-layered samples, this advantage decreases after coffee thermal cycling. These findings parallel the hardness loss observed in all samples after aging with the sour cherry juice and cola content used in the present study. The significant decrease in microhardness observed over time indicates that external factors, such as liquid penetration and low pH, can weaken the polymer structure and deteriorate its mechanical properties.[35] This is because the organic acids and sugar derivatives in the low-pH solutions used in the current

Table 5. Time-Dependent Comparison of Color Difference Across Groups

	ΔE_1 (Day 7)	ΔE_2 (Day 21)	*r*	Test Statistic	*P*
50-WC-C	0.650 (0.257-3.221)	1.479 (0.439-4.008)	0.802	15.000	**.033**[y]
50-WC-Ch	1.885 ± 1.109	1.732 ± 1.345	0.464	0.430	.675[x]
50-LC-C	1.441 (0.395-6.373)	1.458 (0.304-4.722)	0.56	54.000	.588[y]
50-LC-Ch	1.145 ± 0.663	1.427 ± 0.624	0.052	−1.147	.274[x]
100-WC-C	1.806 ± 1.06	2.285 ± 0.861	−0.157	−1.222	.243[x]
100-WC-Ch	1.516 ± 0.642	1.571 ± 0.53	0.187	−0.251	.806[x]
100-LC-C	1.442 ± 0.939	1.208 ± 0.688	−0.438	0.609	.554[x]
100-LC-Ch	0.77 (0.325-1.817)	0.838 (0.357-3.683)	0.264	89.000	.601[y]

Mean ± SD, Median (Minimum-Maximum).
C, Cola; Ch, sour cherry juice; LC, light-cured; WC, water-cured; ΔE, color difference.
[x]Paired samples *t*-test.
[y]Wilcoxon test.

study may have caused the weakening of hydrogen bonds in the resin matrix and the dissolution of interchain connections, increasing the loss of microhardness over time.[20] Acidity chemically reacts with the acrylic resin to fill the gaps between the polymer chains, which leads to the separation of the polymer chains.[11] This situation reveals that low-pH environments can weaken the polymer structure and lead to deterioration of its mechanical properties. After aging, it was observed that the decrease in microhardness values was more pronounced in samples with a thin layer thickness. In a study, no significant reduction in microhardness values was detected after 24 hours of water storage in 3D-printed samples produced with a layer thickness of 100 μm, while a decrease in hardness values was recorded after exposure to water in samples with 50 μm and 25 μm thicknesses. These findings suggest that the polymer structure may be more resistant to environmental effects due to the structures obtained with thicker layers, which contain fewer layer interfaces.[36] However, the fact that the light-curing method produces higher hardness values compared to water curing can be associated with a more effective photopolymerization process.[37]

CONCLUSION

The findings of this study revealed that production parameters, such as layer thickness and curing method, have a significant effect on the surface and optical properties of PMMA-based materials produced by 3D printing. Surface roughness increased, and microhardness decreased over time in all groups. Roughness increase and hardness loss were more pronounced in samples with a thin layer thickness (50 μm) and aqueous curing. Color change was found to be significant in limited groups. The data indicate that selecting the layer thickness and curing method during the production process should be carefully planned, particularly in consideration of long-term clinical use and aesthetic requirements. Therefore, a combination of appropriate production parameters is recommended to obtain high-performance and biostable restorations in PMMA-based prosthesis materials obtained by 3D printing.

There are some limitations to this study. First, only 1 type of PMMA-based 3D printing resin was used in the study; resin types or compositions from different manufacturers were excluded from the evaluation. Additionally, only 2 different layer thicknesses and 2 curing methods were examined. Other production parameters and curing time were kept constant. Only 2 low-pH beverages, such as cherry juice and cola, were preferred as aging protocols, and drinks with different pH ranges and chemical compositions, or those subjected to thermal cycling, were not applied. For these reasons, it is recommended that different material types, production parameters, and aging conditions be considered in further studies to generalize the findings to a broader clinical spectrum.
The results of this study indicate that the production parameters should be carefully optimized to achieve the clinical success of PMMA-based materials produced using 3D printing. The appropriate selection of printing parameters will contribute to obtaining more durable restorations in terms of both aesthetics and functionality, especially in pediatric or long-term use cases.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Ethics Committee Approval: N/A

Informed Consent: N/A

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – Z.O., B.T.; Design – Z.O.; Supervision – Z.O., B.T.; Resources – Z.O.; Materials – Z.O.; Data Collection and/or Processing – B.T.; Analysis and/or Interpretation – Z.O.; Literature Search – B.T.; Writing – Z.O., B.T.; Critical Review – Z.O., B.T.

Declaration of Interests: The authors have no conflicts of interest to declare.

Funding: The authors declared that this study has received no financial support.

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