Heliyon 10 (2024) e24950

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Effect of different production techniques on the color of porcelain-fused-to-titanium restorations

Cumhur Korkmaz

Department of Prosthodontics, Hamidiye Faculty of Dentistry, University of Health Sciences, Istanbul, Turkey

ARTICLE INFO

Keywords:
CIEDE2000
Color
Titanium
Spectrophotometer
Metal ceramic alloys

ABSTRACT

In dentistry, the shade selection of the restoration affects the success of the restoration. For this reason, it may be decisive for clinicians to determine whether the difference in framework production influences color in metal-ceramic restorations. The study examined the effects of different framework production techniques used in porcelain-fused-to-titanium restorations on color changes. 45 square-shaped samples were manufactured using cast, milling, and laser-sintering techniques. Opaque and dentin porcelain were performed, and all samples were glazed. A spectrophotometer was used for color measurements. Before opaque application, after opaque application, and after porcelain + glaze application, it was obtained L*, a*, and b* values. Color differences (ΔE_{00}) were calculated with the CIEDE2000 formula. ANOVA (Post Hoc: Bonferroni) and Shapiro Wilks (Normality) tests were used for statistical analysis ($p < 0.05$). At the different laboratory steps, the difference between cast&laser-sintered groups and between milled&laser-sintered groups was statistically significant ($p < 0.05$). Before and after opaque application, the differences in L*, a*, and b* values between cast, milled, and laser-sintered groups were statistically significant ($p < 0.05$). Different framework production methods influenced the color of porcelain-fused-to-titanium restorations.

1. Introduction

Porcelain-fused-to-metal (PFM) crowns are still an important treatment option for prosthetic dentistry [1]. Noble metal alloys have been used in dental restorations as frameworks due to their excellent mechanical properties, low weight, low thermal conductivity, ideal biocompatibility, and eminent metal-porcelain bond strength [2]. On the other hand, these alloys have been replaced by base metal alloys because of their high cost [2,3]. Although base metal alloys have superior mechanical properties, their poor biocompatibility, low corrosion resistance, and allergenic properties have increased the interest in titanium in prosthetic treatments [4,5]. Titanium is a suitable material for dental restorations because of its excellent biocompatibility, high physical and mechanical properties, low density, and superior corrosion resistance [6–8]. Due to these advantages, titanium has become a suitable material option for patients who have metal allergies, especially [9].

In the manufacture of cast metal frameworks are widely used the lost-wax technique [4]. Although it is mostly preferred in titanium casting today, some problems such as shrinkage, porosity, and the reaction of titanium alloys with the investment material may be encountered [10,11]. Therefore, different methods such as Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) technology and laser-sintering are used to manufacture titanium restorations [11–14]. The CAD-CAM system has the advantages of not requiring any additional procedure and not forming an α-case layer between titanium and porcelain, which affects the bond strength.

E-mail address: cumhur.korkmaz@sbu.edu.tr.

https://doi.org/10.1016/j.heliyon.2024.e24950
Received 8 September 2023; Received in revised form 16 January 2024; Accepted 17 January 2024

The disadvantages of this system are that the manufacturing takes a long time, lacks depth, and quits remarkable material waste after the process [15].

Laser sintering technology is a new system that enables direct material production from different metal alloys without the need for any additional cost or processing. It has also been used safely in the framework producing of porcelain-fused-to-titanium restorations. Laser sintering is a process based on the principle that the laser beam melts a metal alloy powder bed following a path determined by CAD digital files. The system automatically closes after the production process is completed [16]. The most important issue in porcelain-fused-to-metal (PFM) restorations is the resistant bonds between the materials forming the structure. Insufficient bonding between the metal substructure and the porcelain superstructure causes separation and fracture. This causes both aesthetic and functional problems. The incompatibility of coefficients of thermal expansion (CTE) between titanium and porcelain and the formation of a thick oxide layer causes the bond strength on the titanium surface to decrease [17]. Since titanium has a lower coefficient of thermal expansion (8.4 × 10−6/°C) compared to metal alloys (13-16 × 10-6/°C), it occurs bonding problems in porcelain-fused-to titanium (PFT) [10]. To prevent thick oxide layer formation and minimize the CTE difference between titanium and porcelain is used low-fusing porcelain [18,19]. Nanocoating of titanium surfaces with SiO2 and TiO2 using the atomic layer deposition method enables the titanium-porcelain bond to be increased [20].

One of the important factors in the success of PFM restorations is also color. Although the metal framework increases the durability of PFM restorations, the presence of metal negatively affects aesthetic properties by reducing translucency and light transmission [21]. In metal-supported restorations, an opaque porcelain layer is applied before applying dentin porcelain to mask the grayish tone of the underlying metal as it the different from metal-free materials. It has been stated that the color of metal-ceramic restorations is affected by the framework alloy type, the porcelain and cement color [21]. It has been reported that the use of different metal alloys in PFM restorations causes color differences. Brewer et al. [22], in their study where they evaluated the color changes at different stages of PFM restorations using three different metal frameworks, stated that a minor color change occurred after opaque application, and a major color change occurred after the porcelain was fired. The authors assessed that these measured changes may be due to alloy differences [22]. Evaluation of color matching can be done qualitatively or quantitatively [23]. L*, a*, and b* color values of restorations and teeth are used in the color difference calculation. Whether the color difference is perceptible or acceptable is determined by comparing the color perceptibility and color acceptability thresholds [24]. The CIE L*a*b* color system is an international standard developed by the International Commission on Illumination for color measurement. Hue (h) refers to the name of the color in the color spectrum, and Chroma (Ch) refers to the degree of the amount of color. Value (L*) is the lightness-darkness of the color. a* negative value refers to the greenness ratio, positive value redness ratio; b* negative value refers to the blueness ratio, positive value yellowness ratio [25].

Shade selection can be done visually with the observer or digitally using various devices such as colorimeters and spectrophotometers [26]. The most preferred system in digital color measurements today is the CIEDE2000. International color scientists developed the CIEDE2000 formula to determine acceptability and perceptibility more accurately by determining the coefficient of the factor that affects the perception of the eye [27,28].

This study aimed to compare the effects of different framework manufacturing techniques on the color changes of PFT restorations at different laboratory steps. The null hypothesis of the study was that the difference in the framework production technique in PFT restorations would not cause color differences after the laboratory steps.

2. Material and methods

45 square samples (10x10 × 1mm) were manufactured using cast, milling, and laser-sintering techniques. The production techniques and materials used in this study are shown in Table 1.

15 samples were cast with titanium grade 1 (Tritan, Dentaurum, Ispringen, Germany) by using the lost-wax method. The casting of the samples was performed with a special investment material (Rematitan Plus, Dentaurum, Ispringen, Germany). According to the manufacturer's recommendations, the casting rings were placed for the wax elimination process in a preheating furnace and cast with a vacuum device (Rematitan, Dentaurum, Germany). After that, the casting rings were slowly allowed to cool at room temperature. Casting surpluses were abraded with a carbide cutter (Changzhou Lihao Tools Co., Ltd., Jiangsu, China).

15 samples were manufactured from a block of pure titanium by using the CAD/CAM system. (DC-Titan, DCS Dental AG, Allschwil, Switzerland). Sample geometry was created by using CAD software and the data of the samples were sent to the CAM unit for manufacturing.

15 samples were produced in pieces formed layer-by-layer adding with the EOSINT M 290 system (EOS GmbH, Munich, Germany). The EOSINT M 290 is a device that has advanced hardware and software control, using a focused laser beam. In the study, EOS Titanium Ti64 powder was melted and fused into a solid piece by the EOSINT M 290 machine. Thus, samples were automatically manufactured from 3D CAD data without requiring manual manipulation.

Table 1

Production techniques of titanium frameworks and materials.

Production Technique	Product name	Manufacturer	Composition
Milling	DC Titan	DCS Dental AG, Allschwil, Switzerland	Titanium, Grade 2
Casting	Tritan	Dentaurum, Ispringen, Germany	Titanium, Grade 1
Laser-sintering	EOS-Titanium	EOS GmbH, Munich, Germany	Ti64, Grade 5

The bonding surfaces of the samples were polished with 600-grit silicon carbide papers (Sankyo Rikagaku Co., Ltd., Saitama, Japan) under water cooling by a polisher machine (Ecomet 30, Buehler, Germany). The dimensions of all samples were measured from 6 different points with a digital caliper (Digital Caliper, World Precision Instruments, Sarasota, FL, USA), and those that were not suitable were reproduced.

Super Porcelain Ti 22 (Kuraray Noritake Dental Inc., Japan) was used as the veneering porcelain (A1, body shade). Airborne particle abrasion was applied for 15 s at 3.5 bar pressure with 50-μm aluminum oxide to all samples and ultrasonically cleaned in acetone solution for 10 min. Then, the samples were fired at 500 °C–800 °C with a heat rate of 50 °C/min, and a holding time of 3 min under a vacuum of 99 kPa for the oxidation procedure of titanium (Sintra Shenpaz Industries Ltd., Tel Aviv Israel). It was applied bonding porcelain on the surface of the frameworks and fired at 800 °C under a vacuum of 99 kPa. After firing, samples were sandblasted lightly with alumina oxide and cleaned in acetone solution for 5 min. Opaque porcelain was applied on the samples at 0,1 mm thickness (A1, opaque shade) and was fired at 780 °C under a vacuum of 96 kPa. Thicknesses of opaque porcelain of all samples were measured by the coating thickness tester device (Würth, Würth GmbH & Co., Künzelsau, Germany). It was applied porcelain layer at 1 mm thickness was applied to the samples and was fired at 760 °C. Samples larger than 1 mm were ground with sandpaper and glazed.

Color measurements were made by a spectrophotometer under illumination xenon filtered with approximate D65 (Datacolor spectrophotometer, Spectra Flash SF600 Plus, Datacolor AG, Lawrenceville, NJ, USA). CIE L*, a*, and b* values obtained as a result of the measurements were recorded. Mean L*, a*, and b* values were determined by taking the average of 3 measurements obtained from each sample, and the results were recorded. Color measurements were performed in three steps before opaque application, after opaque application, and after porcelain + glaze application. Using the CIEDE2000 formula, color difference values (ΔE_{00}) were calculated between different laboratory steps of different production techniques and the same steps of binary groups. CIEDE2000 formula is as follows [27–29].

$$\Delta E_{00} = \left[\left(\Delta L' \Big/ K_L S_L\right)^2 + \left(\Delta C'/K_C S_C\right)^2 + \left(\Delta H'/K_H S_H\right)^2 + R_T\left(\Delta C'/K_C S_C\right)\left(\Delta H'/K_H S_H\right) \right]^{1/2}$$

ΔL', ΔH', and ΔC' refer to differences in lightness, hue, and chroma. K_L, K_H, and K_C are parametric factors and were used to correct the illuminating and viewing conditions and their value was set to 1.0. The symbols S_L, S_C, and S_H represent weighting functions for the lightness, chroma, and hue components. R_T (rotation term) is used to improve hue and chroma performance in the blue region [30].

Microsoft Excel computer program and PSPP statistical software (GNU Software, General Public License) were used. The results of the study were evaluated at the 95 % confidence interval, at the $p < 0.05$ statistical significance level. In the analysis of data, descriptive analyses (mean, standard deviation, 95 % CI) were used. ANOVA (Post Hoc: Bonferroni) and Shapiro Wilks (Normality) tests were applied.

3. Results

The evaluation ΔE_{00} values of the titanium frameworks manufactured by different techniques, between different laboratory steps, and between the same laboratory steps of the binary groups are presented in Table 2.

When the ΔE_{00} values before opaque application and after opaque application were compared, no statistically significant difference was found between the cast/milled groups ($p = 0.211$) ($p > 0,05$). However, differences between the cast/laser-sintered ($p = 0.001$) and milled/laser-sintered ($p = 0.001$) groups were found significant ($p < 0,05$). When comparing after opaque application and after porcelain + glaze application values, the difference between milled/laser-sintered groups ($p = 0.02$) was found statistically significant ($p < 0,05$). However, the differences between the cast/milled ($p = 0.256$) and cast/laser-sintered ($p = 0.776$) groups were not significant ($p > 0,05$). When comparing before opaque application and after porcelain + glaze values, the differences between the cast/laser-sintered ($p = 0.001$) and milled/laser-sintered ($p = 0.001$) groups were found significant ($p < 0,05$). However, the difference

Table 2

Comparison of the color difference values (ΔE_{00}) between the same steps of the pairwise groups and between the different laboratory steps of the specimens produced by different methods.

ΔE_{00}	Before the opaque app.[a]	After opaque app.[b]	After the porcelain + glaze app.[c]	a-b	a-c	b-c
Cast&Milled(1)	2796 ± 1780 (1,81-3781)	1931 ± 0,895 (1435–2427)	2431 ± 1157 (1,79-3072)	0,211	0,82	0,256
Cast&Laser-sintered(2)	6343 ± 1449 (5,54-7146)	1846 ± 0,953 (1318–2374)	2188 ± 1390 (1417–2959)	0,001[a]	0,001[a]	0,776
Milled&Laser-sintered(3)	6944 ± 2288 (5677–8211)	1734 ± 1316 (1005–2463)	2806 ± 1159 (2165–3448)	0,001[b]	0,001[b]	0,02[b]
(1)–(2)	0,001[+]	0,885	0,443			
(1)–(3)	0,001[+]	0,178	0,395			
(2)–(3)	0,272	0,443	0,206			

[+]: **ΔE_{00}** Before opaque application is statistically significant between cast&milled and cast&laser-sintered groups, and between cast&milled and milled&laser-sintered groups. ($p < 0,05$).

[a] **ΔE_{00}** Laser-sintered group is statistically significant before and after opaque application, before opaque application, and after porcelain + glaze application. ($p < 0,05$).

[b] **ΔE_{00}** The Milled and laser-sintered group is statistically significant before and after opaque application, after opaque application, after porcelain + glaze application and, before opaque application and, after porcelain + glaze application. ($p < 0,05$).

between cast/milled ($p = 0.82$) groups was not significant ($p > 0,05$).

When the ΔE_{00} values were compared between the same steps of the binary groups; before opaque application, it was found statistically significant differences between the cast&milled/cast&laser-sintered groups ($p = 0.0001$) and between cast&milled/milled&laser-sintered groups ($p = 0,0005$) ($p < 0,05$). However, after opaque and porcelain + glaze applications, the differences between groups were not found statistically significant ($p > 0,05$).

L*, a*, and b* values and standard deviations of the different laboratory steps of samples are shown in Table 3. When L*, a*, and b* values of groups are compared; before opaque application and after opaque application, the differences between cast, milled, and laser-sintered groups were found statistically significant ($p < 0,05$). After porcelain + glaze application, there was a statistically significant difference between a* values ($p < 0.05$), while the difference between L* and b* values was not significant ($p > 0.05$).

When L*, a*, and b* values were compared in the same laboratory steps of binary groups; before opaque application, the differences between cast&laser-sintered, cast&milled, and milled&laser-sintered groups were found statistically significant ($p < 0.05$). After opaque application, in terms of L* values, differences between the milled/laser-sintered and cast/milled groups were found statistically significant ($p < 0.05$). Also, in terms of a* and b* values, differences between the groups were statistically significant ($p < 0.05$). After porcelain + glaze application, statistically significant differences were found between the cast/milled and cast/laser-sintered groups in terms of a* values, but no significant differences between the groups in terms of L* and b* values were found ($p > 0.05$).

4. Discussion

In this research, it was investigated the effect of different framework production techniques on the color of porcelain-fused-to-titanium restorations after laboratory steps. According to the results of this research; when evaluated in terms of ΔE00 values, before opaque application/after opaque application and before opaque application/after porcelain + glaze application, the differences between the cast/laser-sintered and milled/laser-sintered groups were statistically significant ($p < 0.05$). Before opaque application, the differences between the cast&milled/cast&laser-sintered and cast&milled/milled&laser-sintered groups were statistically significant ($p < 0.05$), but no significant difference was found between groups after porcelain + glaze application ($p > 0.05$). The null hypothesis that different framework fabrication techniques would not cause color differences in porcelain-fused-to-titanium restorations after laboratory steps was partially rejected.

In a study conducted, it was stated that there are differences in the surface morphologies of titanium frameworks obtained by different manufacturing techniques such as casting and laser sintering [16]. It was evaluated that the color difference between the binary groups before opaque application may be due to differences in surface morphologies in the study.

When studies on the color of PFM restorations are searched in the literature, studies are comparing the color changes of noble alloys and base metal alloys such as Ni-Cr and Co–Cr [22,31]. Crispin et al. [32] stated that there was no significant difference in color change between Au–Pd alloys and high gold alloys in their study. Brewer et al. [22] searched the color changes in dental porcelain baked on Ni–Cr, high gold, and Ag–Pd alloys and stated that the color changes of porcelain fired on Ag–Pd alloy were significantly different from porcelain fired on high gold and Ni–Cr alloys. However, no study has been found in the literature investigating the color changes of PFT restorations produced using different framework methods. In this study, the effect of different framework production methods on the color of the PFT restoration at different laboratory steps was investigated.

Shade matching is a very important issue in the long-term clinical success of PFT restorations and meeting aesthetic expectations. The main problem in this regard is the structural difference such as translucency between natural teeth and porcelain-fused-to-metal restorations [33]. Barghi et al. [34] stated that the thickness of the opaque porcelain layer affected the final color of the porcelain at porcelain-fused-to-metal. Terada et al. [35] found that the opaque porcelain layer is more effective in concealing noble alloys compared to Ni–Cr alloys. They observed that the true color of opaque porcelain becomes apparent when the porcelain thickness exceeds 0.3 mm. Vichi et al. [36] emphasized the significance of the opaque layer thickness in achieving a proper color match for porcelain-fused-to-metal restorations. In the present study, shade A1 opaque porcelain, with a thickness of 0.1 mm, was applied to each sample to detect even minor color variations.

CIE color system is defined on 3 different axes as L*, a*, and b* values. The L* value indicates the lightness/darkness character of the object. Light-colored objects have higher L* values, dark colored objects have lower L* values. The a* and b* coordinates show the chromatic character of the color. The a* value shows the redness-greenness ratio of the color, and the b* value shows the yellowness-blueness ratio. If the a* value is positive, it means redness; if it is negative, it means greenness; If the b* value is positive, it indicates yellowness, and if negative, it indicates blueness [25]. This study found statistically significant differences in L*, a*, and b* values between cast, milled, and laser-sintered groups before and after opaque application ($p < 0,05$). It was found a statistically significant difference between a* values after porcelain + glaze application ($p < 0,05$), but no significant difference was found between L* and b* values ($p > 0,05$). While the lowest L* value was found in the laser-sintered group before the opaque application and after the porcelain + glaze application, the lowest value after the opaque application was found in the cast group. In all three production techniques, it was observed that L* values increased after the opaque application and decreased after the porcelain + glaze application. It is thought that the reason for this is that repeated firing after porcelain and glaze applications reduces the brightness. For all three sample groups, while values approaching red were found in terms of a* values before opaque application, color values approaching green were detected after opaque application and after porcelain + glaze applications. Color changes approaching yellow in terms of b* values were observed in all groups before opaque application, after opaque application, and after porcelain + glaze applications.

Shade selection may differ depending on the ambient light, the characteristics of the material, and the evaluation of the person [37]. To minimize these differences, digital color-measuring devices are used, and spectrophotometers are considered the most reliable of these developed color-measuring devices [38]. In many studies on color difference, the CIE L*a*b system is generally used [39].

Table 3
L[a], a[a], b[a] values and standard deviations for different applications.

	Before Opaque Application			After Opaque Application			After Porcelain + Glaze Application		
	L	a	b	L	a	b	L	a	b
Cast[a]	66,479 ± 2622	1467 ± 0,1	5237 ± 0,258	78,764 ± 1764	−0,784 ± 0,273	9032 ± 0,938	65,875 ± 2103	−0,717 ± 0,155	6817 ± 0,613
	(65,027–67,931)	(1412–1522)	(5095-5,38)	(77,787–79,741)	(−0,936–0,633)	(8513–9551)	(64,710–67,040)	(−0,803-0,631)	(6477–7157)
Milled[b]	69,303 ± 2,15	0,993 ± 0,115	4377 ± 0,463	81,018 ± 0,414	−0,359 ± 0,275	10,858 ± 0,619	64,743 ± 2018	−0,604 ± 0,109	7221 ± 0,545
	(68,112–70,494)	(0,929–1057)	(4121–4634)	(80,789–81,248)	(−0,511–0,206)	(10,515–11,201)	(63,626–65,861)	(−0,665-0,544)	(6919–7522)
Laser-sintered	52,424 ± 2138	0,529 ± 0,12	0,531 ± 0,613	80,104 ± 1507	−0,029 ± 0,176	11,58 ± 0,491	64,431 ± 2092	−0,526 ± 0,096	7239 ± 0,419
	(51,24–53,608)	(0,462–0,595)	(0,192-0,87)	(79,651–80,556)	(−0,127-0,069)	(11,308–11,852)	(63,273-65,59)	(−0,579-0,472)	(7007–7471)
a-b-c	0,0001[a]	0,0001[a]	0,0001[a]	0,0001[a]	0,0001[a]	0,0001[a]	0,146	0,0001[a]	0,060
a-b	0,005	0,0001	0,0001	0,001	0,0001	0,0001	0,427	0,047[c]	0,132
a-c	0,0001	0,0001	0,0001	0,779[b]	0,0001	0,0001	0,190	0,0001[c]	0,107
b-c	0,0001	0,0001	0,0001	0,0001	0,002	0,024	0,999	0,258	0,999

[a] Statistically significant (ANOVA).

[b] After opaque application, the difference between cast&laser-sintered groups for L* values were not statistically significant ($p > 0.05$).

[c] The difference between cast-milled and cast-laser-sintered for a* value after porcelain + glaze application was found to be statistically significant ($p < 0.05$).

However, the CIEDE 2000 system can also detect low color differences in dental color science [28]. In this study, for color measurements of all specimens used a spectrophotometer (Datacolor spectrophotometer, Spectra Flash SF600 Plus, Datacolor AG, Lawrenceville, NJ, USA), and the color difference values were calculated with the CIEDE2000 formula.

Paravina et al. [24] CIEDE2000 reported the 50 % perceptibility threshold value as 0.81 and the acceptability threshold value as 1.77, and the same values were used in this study to compare color changes (ΔE_{00}). In the study, it was determined that the color change between the milled and laser-sintered groups after the opaque application was acceptable ($\Delta E_{00} = 1.73$), and when comparing all other groups, the color changes were perceptible and above the acceptable thresholds.

In this research, we examined the impact of various techniques for producing frameworks in porcelain-fused-titanium restorations on color changes. The measurements were conducted using a spectrophotometer before opaque application, after opaque application, and after porcelain + glaze application. It's important to note that a limitation of this study is the use of only A1 color porcelain. Additionally, variations in metal alloys and different opaque and porcelain thicknesses are factors that could influence the outcomes. To enhance our understanding, future investigations should explore the effects of diverse opaque and porcelain thicknesses, as well as consider different shades of porcelain.

5. Conclusions

Taking into account the limitations of this study, the following conclusions can be derived.

1. Different framework production methods affect the color of porcelain-fused-to-titanium restorations after different steps of laboratory procedures.
2. While the lowest L* value was found in the laser-sintered group before the opaque application and after the porcelain + glaze application, the lowest value after the opaque application was found in the cast group.
3. For all three sample groups, while values approaching red were found in terms of a* values before opaque application, color values approaching green were detected after opaque application and after porcelain + glaze applications.
4. Color changes approaching yellow in terms of b* values were observed in all groups after the laboratory processes.
5. Cast and milling methods used as framework production techniques in porcelain-fused-to-titanium restorations have produced optically better results than the laser-sintering method.

Funding

This research did not receive any specific funding.

CRediT authorship contribution statement

Cumhur Korkmaz: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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.

Acknowledgments

None.

References

[1] M. Behr, F. Zeman, T. Baitinger, J. Galler, M. Koller, G. Handel, M. Rosentritt, The clinical performance of porcelain-fused-to-metal precious alloy single crowns: chipping, recurrent caries, periodontitis, and loss of retention, Int. J. Prosthodont. (IJP) 27 (2014) 153–160, https://doi.org/10.11607/ijp.3440.

[2] K.J. Anusavice, Phillips' Science of Dental Materials, eleventh ed., W.B. Saunders, Philadelphia, 2003, pp. 621–654.

[3] H. Yilmaz, C. Dinçer, Comparison of the bond compatibility of titanium and a NiCr alloy to dental porcelain, J. Dent. 27 (3) (1999) 215–222, https://doi.org/10.1016/s0300-5712(98)00045-14.

[4] R.R. Wang, A. Fenton, Titanium for prosthodontic applications: a review of the literature, Quintessence Int. 27 (6) (1996) 401–408.

[5] K. Akagi, Y. Okamoto, T. Matsuura, T. Horibe, Properties of test metal ceramic titanium alloys, J. Prosthet. Dent 68 (3) (1992) 462–467, https://doi.org/10.1016/0022-3913(92)90411-3.

[6] H. Koizumi, Y. Takeuchi, H. Imai, T. Kawai, T. Yoneyama, Application of titanium and titanium alloys to fixed dental prostheses, J Prosthodont Res 63 (3) (2019) 266–270, https://doi.org/10.1016/j.jpor.2019.04.011.

[7] K. Suzuki, T. Takano, S. Takemoto, T. Ueda, M. Yoshinari, K. Sakurai, Influence of grade and surface topography of commercially pure titanium on fatigue properties, Dent. Mater. J. 37 (2) (2018) 308–316, https://doi.org/10.4012/dmj.2017-125.

[8] A. Ogunc, G. Yildirim Avcu, Effect of repeated firings on the marginal and internal adaptation of implant-supported metal-ceramic restorations fabricated with different thicknesses and fabrication methods, J. Prosthet. Dent 125 (3) (2021), https://doi.org/10.1016/j.prosdent.2020.10.021.

[9] D. Leong, J. Chai, E. Lautenschlager, J. Gilbert, Marginal fit of machine-milled titanium and cast titanium single crowns, Int. J. Prosthodont. (IJP) 7 (5) (1994) 440–447.

[10] A. Sadeq, Z. Cai, R.D. Woody, A.W. Miller, Effects of interfacial variables on ceramic adherence to cast and machined commercially pure titanium, J. Prosthet. Dent 90 (1) (2003) 1–17, https://doi.org/10.1016/s0022-3913(03)00263-4.

[11] P. Haag, K. Nilner, Questions and answers on titanium-ceramic dental restorative systems: a literature study, Quintessence Int. 38 (1) (2007) e5–e13.

[12] S. Papadiochou, A.L. Pissiotis, Marginal adaptation and CAD-CAM technology: a systematic review of restorative material and fabrication techniques, J. Prosthet. Dent 119 (4) (2018) 545–551, https://doi.org/10.1016/j.prosdent.2017.07.001.

[13] M.A. Aslan, C. Ural, S. Arici, Investigation of the effect of titanium alloy surface coating with different techniques on titanium-porcelain bonding, J. Prosthet. Dent 115 (1) (2016) 115–122, https://doi.org/10.1016/j.prosdent.2015.07.004.

[14] M. Antanasova, A. Kocjan, M. Hočevar, P. Jevnikar, Influence of surface airborne-particle abrasion and bonding agent application on porcelain bonding to titanium dental alloys fabricated by milling and by selective laser melting, J. Prosthet. Dent 123 (3) (2020) 491–499, https://doi.org/10.1016/j.prosdent.2019.02.011.

[15] U. Iseri, Z. Ozkurt, E. Kazazoglu, Shear bond strengths of veneering porcelain to cast, machined and laser-sintered titanium, Dent. Mater. J. 30 (3) (2011) 274–280, https://doi.org/10.4012/dmj.2010-101.

[16] T. Akova, Y. Ucar, A. Tukay, M.C. Balkaya, W.A. Brantley, Comparison of the bond strength of laser-sintered and cast base metal dental alloys to porcelain, Dent. Mater. 24 (10) (2008) 1400–1404, https://doi.org/10.1016/j.dental.2008.03.001.

[17] J. Bieniaś, B. Surowska, A. Stoch, H. Matraszek, M. Walczak, The influence of SiO2 and SiO2-TiO2 intermediate coatings on bond strength of titanium and Ti6Al4V alloy to dental porcelain, Dent. Mater. 25 (9) (2009) 1128–1135, https://doi.org/10.1016/j.dental.2009.01.107.

[18] M. Könönen, J. Kivilahti, Fusing of dental ceramics to titanium, J. Dent. Res. 80 (3) (2001) 848–854, https://doi.org/10.1177/00220345010800030101.

[19] S. Atsü, S. Berksun, Bond strength of three porcelains to two forms of titanium using two firing atmospheres, J. Prosthet. Dent 84 (5) (2000) 567–574, https://doi.org/10.1067/mpr.2000.110267.

[20] S.S. Atsu, M.E. Aksan, A.C. Bulut, F. Tamimi, The effect of nanocoatings of SiO_2, TiO_2, and ZrO_2 on titanium-porcelain bonding, J. Prosthet. Dent 126 (2) (2021), https://doi.org/10.1016/j.prosdent.2021.04.023, 222.e1-222.e8.

[21] S.G. Kourtis, A.P. Tripodakis, A.A. Doukoudakis, Spectrophotometric evaluation of the optical influence of different metal alloys and porcelains in the metal-ceramic complex, J. Prosthet. Dent 92 (5) (2004) 477–485, https://doi.org/10.1016/j.prosdent.2004.08.012.

[22] J.D. Brewer, C.K. Akers, D.A. Garlapo, S.E. Sorensen, Spectrometric analysis of the influence of metal substrates on the color of metal-ceramic restorations, J. Dent. Res. 64 (1) (1985) 74–77, https://doi.org/10.1177/00220345850640011501.

[23] F.D. Jarad, B.W. Moss, C.C. Youngson, M.D. Russell, The effect of enamel porcelain thickness on color and the ability of a shade guide to prescribe chroma, Dent. Mater. 23 (4) (2007) 454–460, https://doi.org/10.1016/j.dental.2006.03.001.

[24] R.D. Paravina, R. Ghinea, L.J. Herrera, et al., Color difference thresholds in dentistry, J Esthet Restor Dent 27 (Suppl 1) (2015) S1–S9, https://doi.org/10.1111/jerd.12149.

[25] Comission Internaciaonale de l'Eclairage, Colorimetry: Official recommendations of the International Commission on Illumination, Bureau Central de la CIE, Paris, Publication CIE, 1976, 15.

[26] A.J. Hassel, A.C. Grossmann, M. Schmitter, Z. Balke, A.M. Buzello, Interexaminer reliability in clinical measurement of L*C*h* values of anterior teeth using a spectrophotometer, Int. J. Prosthodont. (IJP) 20 (1) (2007) 79–84.

[27] CIE, Improvement to Industrial Color-Difference Evaluation, Central Bureau of the CIE Vienna, CIE, 2001. Publication No. 142.

[28] R. Ghinea, M.M. Pérez, L.J. Herrera, M.J. Rivas, A. Yebra, R.D. Paravina, Color difference thresholds in dental ceramics, J. Dent. 38 (Suppl 2) (2010) e57–e64, https://doi.org/10.1016/j.jdent.2010.07.008.

[29] M.R. Luo, G. Cui, B. Rigg, The development of the CIE 2000 color-difference formula: CIEDE2000, Color Res. Appl. 26 (2001) 340–350.

[30] CIE Technical Report, Colorimetry, CIE Central Bureau, Vienna, Austria, 2004. Publication No. 15.3.

[31] S.G. Kourtis, A.P. Tripodakis, A.A. Doukoudakis, Spectrophotometric evaluation of the optical influence of different metal alloys and porcelains in the metal-ceramic complex, J. Prosthet. Dent 92 (5) (2004) 477–485, https://doi.org/10.1016/j.prosdent.2004.08.012.

[32] B.J. Crispin, R.R. Seghi, H. Globe, Effect of different metal ceramic alloys on the color of opaque and dentin porcelain, J. Prosthet. Dent 65 (1991) 351–356.

[33] L. Miller, Shade matching, J Esthet Dent 5 (1993) 143–153.

[34] N. Barghi, R.E. Lorenzana, Optimum thickness of opaque and body porcelain, J. Prosthet. Dent 48 (1982) 429–431.

[35] Y. Terada, T. Sakai, R. Hirayasu, The masking ability of an opaque porcelain: a spectrophotometric study, Int. J. Prosthodont. (IJP) 2 (3) (1989) 259–264.

[36] A. Vichi, G. Corciolani, M. Carrabba, A. Munoz, C. Louca, Influence of thickness of opaque porcelain and alloy color on the final color of porcelain-fused-to-metal restorations, Materials 16 (1) (2023) 457, https://doi.org/10.3390/ma16010457.

[37] A. Joiner, Tooth colour: a review of the literature, J. Dent. 32 (Suppl 1) (2004) 3–12, https://doi.org/10.1016/j.jdent.2003.10.013.

[38] K. Lehmann, A. Devigus, S. Wentaschek, C. Igiel, H. Scheller, R. Paravina, Comparison of visual shade matching and electronic color measurement device, Int J Esthet Dent 12 (3) (2017) 396–404.

[39] J.L.B. de Abreu, C.S. Sampaio, E.B. Benalcázar Jalkh, R. Hirata, Analysis of the color matching of universal resin composites in anterior restorations, J Esthet Restor Dent 33 (2) (2021) 269–276, https://doi.org/10.1111/jerd.12659.