Materials and Design 30 (2009) 445–451

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Comparative evaluation of bond strength of various metal–ceramic restorations

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ARTICLE INFO

Article history:
Received 12 February 2008
Accepted 2 June 2008
Available online 7 June 2008

Keywords:
Non-ferrous metals and alloys (A)
Bonding (D)
Casting (C)

ABSTRACT

The success of the porcelain-fused-to-alloy restoration depends primarily on the bond strength between porcelain and metal substructure. This study evaluated the bonding characteristics of six porcelains fused to three different alloys. The bond strength of the specimens was tested using a 3-point bending test. According to the test results, although the metal–porcelain systems presented statistically significant differences between them ($p < 0.05$), the bending strength values of all metal–porcelain systems were within the acceptable levels (25 N/mm^2) in the DIN 13927. When we compared the bond strength values regarding precious and non-precious alloys, no standard behavior was observed among metal–ceramic systems.

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1. Introduction

The metal-bonded porcelain restoration involves a marrying of the good mechanical properties of cast dental alloys with the excellent esthetic properties of porcelain. The durability and longevity of the metal–ceramic restorations depend on the formation of the bond between metal and porcelain materials [1–4].

The adherence between the ceramic and metal has been attributed to mechanical retention forces [5–7], van der Waal's forces [7,8], chemical bonding by bonding oxides [9–11] and contracting forces by mismatch of expansion coefficients [3,12]. The mechanical bond depends on surface roughness, dovetails, projections, and anchor points [7,13]. The van der Waal's forces would suggest bonding due to electrical dipoles or dispersion effect with no chemical interaction taking place [7]. The chemical bond is dictated by the oxide layer formed on the metal substrate that forms ionic, covalent, or metallic bonds with oxides in the ceramic opaque [7,9–11,14,15]. Compressive bonding forces result from differences in the thermal expansion of the ceramic and metal substrate [3,4,12,14,16].

The important requirement of the alloy used to form the substructure is that the alloy should have a value of coefficient of thermal expansion similar to that for the porcelain to which it is bonded [3,4]. If the metal and the ceramic have different thermal expansion coefficients, the two materials will contract at different rates during cooling and strong residual stresses will form across the interface. If these stresses are strong enough, the porcelain on the porcelain-fused-to-metal restorations will crack or separate from the metal [3]. When another material is tried with the same porcelain, there is a possibility of a mismatch in the thermal expansion which may result in cracking of the porcelain. However, many dentists and dental technicians use different dental ceramics with different alloys without concerning about the characteristics of compatibility of those materials. de Melo et al. [17] evaluated the shear bond strengths of a ceramic system to alternative alloys. Although it was reported that the highest shear bond strength has been obtained when the ceramic and the metal were manufactured by the same company, no significant difference was reported about the cases whether they are manufactured by the same company or by different companies.

Gold alloys have been used in dentistry as porcelain-fused-to-metal restorations for decades because of their accuracy in the casting process and durability and corrosion resistance in the oral conditions [2]. Due to their low elastic modulus and high costs, alternative alloys were introduced for the fabrication of metal–ceramic restorations [2,18]. Non-precious alloys, such as Ni–Cr and Co–Cr alloys have become popular because of their mechanical properties and low cost [2,3,18].

Many authors [17,19–21] have evaluated the bonding strengths of different alloys to ceramics, using physical tests. Many tests were designed in an attempt to reproduce the complex set of forces which act on the metal–ceramic interface [22–25]. For this reason, there has been a great concern on the evaluation of the bond strength between metal and ceramic, seeking the most ideal test to evaluate this interface, simulating the conditions observed in the oral cavity. Although shear, tensile, flexural and torsion tests have been used to determine bond strength at the interface, no uniformly accepted method for determining bond strengths seems to have evolved [22–26].

As the use of metal–ceramic restorations continues and the new metal alloys and porcelain systems are developed, additional investigation of the metal–ceramic bond is indicated. The purpose of this study was to evaluate and compare the bond strength of

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0261-3069/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.matdes.2008.06.002

metal/porcelain when metals involving different contents were used with different porcelains.

2. Method

Ninety wax patterns having dimensions 25 mm × 3.0 mm × 0.5mm were prepared by a metal mold according to DIN 13927 [27]. In order to obtain flat wax surfaces two glass slabs were applied to each side of the patterns. After each of the wax patterns was connected to a wax sprue which forms channel to allow molten metal to flow into mold, 30 wax patterns were invested with investment material (Bellasun, Bego, Bremen, Germany) and cast into gold-based alloy (BioPontoStar, Bego, Bremen, Germany), 30 wax patterns were invested with investment material (Bellasun Bego, Bremen, Germany) and cast into Ni–Cr alloy (Wiron 99, Bego, Bremen, Germany) and 30 wax patterns were invested with investment material (Bellavest SH, Bego, Bremen, Germany) and cast into Co–Cr alloy (Wirobond C, Bego, Bremen, Germany). The investment materials used in this study are resistant to high casting temperatures and also known as refractory materials. The compositions of the metal alloys are shown in Table 1.

Castings of metal strips were made by an automatic centrifugal casting machine (TS3, Degussa, Germany). After divesting of the castings, sprues were removed and metal strips were cleaned. The cast metal strips were ground with silicon carbide paper to achieve flat and smooth surfaces and to reach the dimensions recommended by DIN 13927. After the surfaces of cast specimens were sand-blasted with 50 μm Al_2O_3 particles (Korox, Bego, Bremen, Germany), they were cleaned with distilled water for 15 min in an ultrasonic bath (Whaledent, Biosonic, Toronto, USA) before bonding to porcelain. All specimens were degassed by pre-heating process to prevent hydrogen absorbed during casting process which induces porosities in the applied porcelain and to create a thin oxide layer to promote a strong chemical bond. Each of these groups consisting of 30 metal strip casts was divided into six groups and six different porcelain systems, which are Finesse (Dentsply Ceramco, Burlington, NJ, USA), IPS d-sign (Ivoclar Vivadent AG/Schaan/Liechtenstein), Ceramco II (Dentsply Ceramco, Burlington, NJ, USA), VMK 95 (Vita Zahnfabrik, Sackingen, Germany), IPS Classic (Ivoclar Vivadent AG/Schaan/Liechtenstein) and Omega 900 (Vita Zahnfabrik, Sackingen, Germany), were fired onto five metal strips of each of these six groups. Opaque and body porcelains were fired according to the manufacturer's instructions. Ceramic firing cycles are shown in Table 2. For the standardization of the samples, all samples were prepared by the same person. For all specimens, the total number of firings was standardized by four firings. Porcelain was applied by plastic jig having dimensions 8 mm × 3 mm × 1.2 mm. After firing, the thickness of the porcelain was adjusted as 1.0 mm by polishing with #320 then #1000 emery papers.

2.1. Bond strength testing

The bond strengths of the specimens were tested using a 3-point bending test as per DIN 13927 [27], with a testing machine (Zwick/Z 020, GmbH and Co, Ulm, Germany). Each metal–ceramic specimen was positioned on the supports (0.25 in. in diameter) of the bending device with the porcelain facing downward to determine tensile stresses which debond the porcelain from the terminal site of one end of the metal ceramic interface toward the other. The distance between supports was arranged to be 20 mm. A compressive load was applied to the mid-point of the metal strip by a 0.25 in. in diameter metal rod at a crosshead speed of 1.5 mm/min. The fracture force F (in Newtons) was measured for specimen's failure by a debonding crack occurring at one end of the ceramic layer. The bond strength (γ) was calculated with the following formula [27]:

$$\gamma\ (\mathrm{MPa}) = F\ (\mathrm{N}) \times K\ (\mathrm{mm}^{-2}).$$

In this formula, F denotes the maximum force leading to failure, K denotes a constant calculated according to the elastic modulus of the metal and the thickness of the specimen.

Table 1
Metal alloys and their compositions (% by weight)

Alloy	Au	Pt	Zn	Fe	Rh	In	Co	Cr	Mo	W	Si	Ce	C	Ni	Nb
BioPontoStar	86	11.5	1.6	0.4	0.3	0.2	–	–	–	–	–	–	–	–	–
Wirobond C	–	–	–	0.5	–	–	61	26	6	5	1	0.5	0.02	–	–
Wiron 99	–	–	–	0.5	–	–	–	22.5	9.5	–	1	0.5	0.02	65	1

Table 2
Ceramic firing cycles

		Pre-drying (°C)	$t\uparrow$ (°C/min)	Firing Temperature (°C)
Finesse	Opaquer firing	450	90	800
	1st dentin firing	450	35	760
	2nd dentin firing	450	35	750
Ceramco II	Opaquer firing	650	70	970
	1st dentin firing	650	70	935
	2nd dentin firing	650	70	930
IPS d-sign	Opaquer firing	400	80	980
	1st dentin firing	400	60	920
	2nd dentin firing	400	60	910
IPS Classic	Opaquer firing	400	80	980
	1st denti0n firing	400	60	920
	2nd dentin firing	400	60	910
VMK 95	Opaquer firing	600	83	930
	1st dentin firing	600	55	930
	2nd dentin firing	600	55	930
Omega 900	Opaquer firing	600	75	900
	1st dentin firing	600	50	900
	2nd dentin firing	600	48	890

2.2. Statistical analyses

The data obtained from the 3-point bending test were grouped according to the alloys. To determine whether there was a statistical significant difference between the mean bond strength values of six different porcelain systems, which were fused to each metal alloy, Kruskal–Wallis statistical test was performed. Kruskal–Wallis test found a statistical difference between the porcelain systems at the 95% confidence level ($p < 0.05$). Mann–Whitney U statistical test was used to compare the mean bond strength values of six different porcelain systems with each other in pairs and to see which porcelain systems show statistically significant difference.

3. Results

3.1. BioPontoStar

The statistical summary of bending test for BioPontoStar is listed in Table 3. Kruskal–Wallis test revealed significant differences between the mean bond strength values obtained between BioPontoStar and six different porcelain systems ($p < 0.05$) (Table 4). Mann–Whitney U test was performed to find which porcelain systems show significant difference (Table 5). According to Mann–Whitney U test, the maximum mean bond strength value was obtained between BioPontoStar-Ceramco II and this bond strength was significantly higher than those obtained for BioPontoStar-Finesse, BioPontoStar-IPS d-sign, BioPontoStar-VMK 95, BioPontoStar-IPS Classic metal–ceramic complexes. Although the bond

Table 3
Statistical summary of bending test for BioPontoStar alloy (MPa)

Porcelain	*n*	Minimum	Maximum	Mean value	Standard deviation
Finesse	5	25.90	53.80	39.90	10.34
IPS d-sign	5	31.80	38.80	35.36	3.01
Ceramco II	5	54.80	75.70	66.44	8.28
Vita VMK 95	5	39.80	58.40	48.74	7.37
IPS Classic	5	38.20	58.90	51.58	8.14
Omega 900	5	42.50	71.50	55.48	10.69

Table 4
The Kruskal–Wallis test results of BioPontoStar alloy

Groups	*n*	Mean rank
Finesse	5	9.20
IPS d-sign	5	4.70
Ceramco II	5	26.60
VMK 95	5	15.30
IPS Classic	5	17.70
Omega 900	5	19.50

$\chi^2 = 19.395$, d.f. = 5, $p = 0.002$.

Table 5
The Mann–Whitney U statistical analysis results of BioPontoStar alloy

	Finesse	IPS d-sign	Ceramco II	VMK 95	IPS Classic	Omega 900
Finesse			a			a
IPS d-sign			a	a	a	a
Ceramco II				a	a	
VMK 95						
IPS Classic						
Omega 900						

[a]Denotes which porcelain groups show statistical difference ($p < 0.05$).

strength of BioPontoStar-Ceramco II was higher than the one for BioPontoStar-Omega 900, this difference was not statistically significant. BioPontoStar-Omega 900 showed significantly higher bond strength than BioPontoStar-Finesse and BioPontoStar-IPS d-sign. Also, BioPontoStar-IPS Classic had significantly higher bond strength than BioPontoStar-IPS d-sign.

3.2. Wirobond C

The statistical summary of bending test for Wirobond C is listed in Table 6. Kruskal–Wallis test revealed significant differences between the mean bond strength values obtained between Wirobond C and six different porcelain systems ($p < 0.05$) (Table 7). Mann–Whitney U test was performed to find which porcelain systems show significant difference (Table 8). According to the results of this test, the maximum mean bond strength value obtained between Wirobond C-Omega 900 was significantly higher than those obtained between Wirobond C-Finesse, Wirobond C-IPS d-sign, Wirobond C-Ceramco II and Wirobond C-VMK 95. Wirobond C-Finesse had significantly higher bond strength than those for Wirobond C-IPS d-sign, Wirobond C-Ceramco II, Wirobond C-VMK95 metal–ceramic complexes. Wirobond C-IPS Classic had significantly higher bond strength than those for Wirobond C-Finesse, Wirobond C-IPS d-sign, Wirobond C-Ceramco II and Wirobond C-VMK 95.

Table 6
Statistical summary of bending test for Wirobond C alloy (MPa)

Groups	*n*	Minimum	Maximum	Mean value	Standard deviation
Finesse	5	52.00	77.00	62.24	9.61
IPS d-sign	5	27.90	47.20	41.16	7.97
Ceramco II	5	37.80	52.00	44.08	6.11
VMK 95	5	37.60	48.40	41.78	4.78
IPS Classic	5	65.70	90.60	76.22	10.07
Omega 900	5	75.20	92.00	85.16	6.34

Table 7
The Kruskal–Wallis test results of Wirobond C alloy

Groups	*n*	Mean rank
Finesse	5	18.70
IPS d-sign	5	7.80
Ceramco II	5	9.30
VMK 95	5	7.00
IPS Classic	5	23.40
Omega 900	5	26.80

$\chi^2 = 23.918$, d.f. = 5, $p = 0.000$.

Table 8
The Mann–Whitney U statistical analysis results of Wirobond C alloy

	Finesse	IPS d-sign	Ceramco II	VMK 95	IPS Classic	Omega 900
Finesse		b	b	b	b	b
IPS d-sign					b	b
Ceramco II					b	b
VMK 95					b	b
IPS Classic						
Omega 900						

[b]Denotes which porcelain groups show statistical difference ($p < 0.05$).

3.3. Wiron 99

The statistical summary of bending test for Wiron 99 is listed in Table 9. Kruskal–Wallis test revealed significant differences between the mean bond strength values obtained between Wiron 99 and six different porcelain systems ($p < 0.05$) (Table 10). Mann–Whitney U test was performed to find which porcelain systems show significant difference (Table 11). According to the results of this test, the maximum mean bond strength value obtained between Wiron 99-Omega 900 was statistically higher than those obtained between Wiron 99-IPS d-sign, Wiron 99-Ceramco II and Wiron 99-VMK 95. Although Wiron 99-Finesse

Table 9
Statistical summary of bending test for Wiron 99 alloy (MPa)

Groups	*n*	Minimum	Maximum	Mean value	Standard deviation
Finesse	5	46.10	62.30	52.18	6.08
IPS d-sign	5	22.30	38.80	31.32	7.27
Ceramco II	5	31.80	51.30	38.82	7.50
VMK 95	5	27.90	43.30	33.70	6.39
IPS Classic	5	37.60	59.20	48.14	8.05
Omega 900	5	36.50	74.60	61.74	15.24

Table 10
The Kruskal–Wallis test results of Wiron 99 alloy

Groups	*n*	Mean rank
Finesse	5	22.00
IPS d-sign	5	7.40
Ceramco II	5	12.20
VMK 95	5	7.40
IPS Classic	5	19.20
Omega 900	5	24.80

$\chi^2 = 18.386$, d.f. = 5, $p = 0.002$.

Table 11
The Mann–Whitney U statistical analysis results of Wiron 99 alloy

	Finesse	IPS d-sign	Ceramco II	VMK 95	IPS Classic	Omega 900
Finesse		c	c	c		
IPS d-sign					c	c
Ceramco II						c
VMK 95					c	c
IPS Classic						
Omega 900						

[c]Denotes which porcelain groups show statistical difference ($p < 0.05$).

had significantly higher bond strength than Wiron 99-IPS d-sign, Wirobond C-Ceramco II, and Wirobond C-VMK 95 metal–ceramic combinations, there was no statistically significant differences between mean bond strength values of Wiron 99-Finesse, Wiron 99-IPS Classic and Wiron 99-Omega 900. Wiron 99-IPS Classic had significantly higher bond strengths than Wiron 99-IPS d-sign and Wiron 99-VMK 95.

4. Discussion

With continually increasing numbers of ceramometal alloys and porcelains becoming commercially available, prediction for the compatibility of various combinations of materials is a great necessity. Most ceramometal restorations are formed with a porcelain produced by one manufacturer and an alloy produced by another. This differential leads to confusion among dental ceramists because each manufacturer has its own recommended firing cycles, which in most instances don't concur with those of other manufacturers. The present investigation was designed to obtain information concerning the influence of the type of alloy and the brand of porcelain relative to bond strength of ceramometal complexes and to provide a guide for a predictable selection of the metal–porcelain combinations.

The success of the metal–porcelain systems are directly related to the bond strengths at the metal–ceramic interfaces [1,3,19,28]. Various tests have been designed and selected by researchers to evaluate the metal–ceramic bond strengths [22–25]. Assuming that shear stresses are generally responsible for the clinical failure of the metal–ceramic interfacial region, Anusavice et al. [29] suggested the parallel shear test as the ideal bond strength test among those available. Using the circular parallel shear test, Papazoglu and Brantley [25] and Gilbert et al. [30] experienced that when the porcelain was embedded in dental stone and the alloy was loaded in macroscopic shear, the crack propagated originally along the interface and finally diverted through the porcelain. Hermann et al. [31] described that when this crack diversion occurs, a higher force is required for crack propagation and higher apparent bond strengths will be induced. Papazoglu and Brantley [25] concluded that the ideal test would actually have only tensile stress components at the interface and no shear components. For measurement of metal–ceramic adherence, or force to failure, the test must cause debonding of the ceramic layer at the interfacial region and not tensile failure of the ceramic due to bending stress developed on its free surface [25]. Since there is no consensus in the literature for the ideal test to evaluate the bond strength of metal–ceramic complexes [3,26] and flexural strength test is considered as the most appropriate method to measure bond strength between two materials [10,14,19,21,25,32,33], we evaluated the bonding characteristics of six commercially available porcelains fused to one gold-based, one Co–Cr and one Ni–Cr alloy, using 3-point bending test which provides consistent and reproducible results as well as easy fabrication of the test samples [22]. This test, which was proposed by Lenz and Kessel [32] measures the critical bending force, F_{fail}, under which debonding of the porcelain from the alloy strip occurs at one of the two ends of the ceramic layer.

Because all of the specimens prepared in this study had identical dimensions, the load at bond failure could be used as a parameter to compare the bond strengths among systems. The bending strength of each metal–porcelain system was found to be higher than the acceptable standard levels (25 N/mm^2) in the DIN 13927 [27].

As was shown in the study of Schweitzer et al. [14], during our experimentation, debonding of the samples initiated from the terminal site of one end of the metal–ceramic interface toward the other. Also, this is compatible with the finite element study of Anusavice et al. [29] which reported that tensile stresses on the metal–ceramic bond are the greatest at the ceramic termination sites.

Although chemical bonding is generally regarded to be responsible for metal–porcelain adherence, evidence exists that mechanical interlocking provides the principal bonding. Lavine and Custer [5] found that surface roughness increased the bond strength as compared with non-roughened castings due to increase in surface area, thus improving wettability, because of the diffusion of the porcelain particles into the metal–porcelain interface. McLean and Sced [6] tested the effects of pre-oxidation, surface roughness and pickling of the substrate after undergoing oxidation and discovered that sandblasting and degassing prior to porcelain application achieved the best bond strength. In our study, sandblasting of the samples with 50 μm aluminum oxide particles and degassing process made before porcelain application seemed to result in higher bond strength values than acceptable values for all metal–porcelain complexes. Sandblasting with 50 μm aluminum oxide was the medium usually used to promote the mechanical retention of metal–ceramic complexes [34].

The service life of a metal–ceramic restoration greatly depends on the residual stresses which can lead to cracking and crazing in the porcelain [35]. These stresses, causing such cracking, are directly proportional to the difference in thermal expansion between the two materials, as well as the magnitude of the temperature drop during cooling [36]. To avoid residual stresses, there must be exact matching of the thermal contraction coefficients (α) of the metal and ceramic below the glass transition temperature (500–600 °C) of the porcelain, where ceramic begins to sustain stresses. This is impossible since α values for the porcelain and alloy do not coincide during cooling [37]. The general consensus is that the alloy should have a slightly higher thermal expansion coefficient than the porcelain in order to produce compressive stresses in the porcelain on cooling [3,34,38]. Generally, a 0.5×10^{-6} °C difference in coefficients is desirable [3]. Vickery and Badinelli [12] concluded that the major attachment force in porcelain-gold prostheses was derived from compression forces generated by differences in the thermal expansion of porcelain and gold. All of the metals tested in the present study were considered thermally compatible with the porcelain systems, as they have the following thermal expansion coefficients (10^{-6} K^{-1}) purported by the manufacturers: BioPontoStar (Au–Pt–Zn), 14.4; Wirobond C (Co–Cr), 14.2; and Wiron 99 (Ni–Cr) 14.0, which are very close to one another. The thermal expansion coefficient of IPS d-sign porcelain system has been indicated by the manufacturer as $12.6 \pm 0.5\ 10^{-6}$ K^{-1}. For IPS Classic, Omega 900 and VMK 95 porcelain systems, thermal expansion coefficients (10^{-6} K^{-1}) has been reported by the manufacturers as 13.2 ± 0.5, 13.4 – 13.9, 13.3 – 13.7, respectively. Finesse ceramic system has been suggested by the manufacturer for metal alloys with a coefficient of thermal expansion (10^{-6} K^{-1}) ranging between 14 and 15.1.

Although bond strength values for each metal–ceramic complex were found higher than the acceptable levels in DIN 13927 [27], statistically significant differences between the mean bond

strength values of them were determined. Walton and O'Brien [39] examined the compound discs and spheres of porcelain bonded to a palladium-silver alloy and found that crack formation in the porcelain was dependent on the difference in the thermal expansion coefficients of porcelain and metal, the geometry and the dimensions of the sample, and porcelain metal thickness ratio. In the present study, since the geometries and the dimensions and porcelain-metal thickness ratio were the same for all samples, differences in the thermal expansion coefficient of porcelain systems and of metal alloys were considered as one of the probable reasons in obtaining different bond strength values. Regardless of the metal systems, we observed the lowest bond strength values with IPS d-sign porcelain system. This is probably due to the lowest thermal expansion coefficient of IPS d-sign porcelain systems, which resulted in the greatest difference in thermal expansion coefficients between metals and IPS d-sign porcelain.

Despite the fact that VMK 95 and Omega 900 porcelain systems have quite similar coefficients of thermal expansion and firing cycles, significant difference between the bond strength values of these porcelain systems was found in our study. This was attributed to the behavior of the individual porcelains. Perhaps, the increased bond strength depends on the increased wettability of the metal by Omega 900 porcelain system. Further investigation of the properties of porcelains, such as the effect of their chemical composition or their physical and microstructural properties at elevated temperatures, would be required to explain the above data.

Many researchers believe that adhesion mechanism between porcelain and metal is related to the formation of metal oxides [3,9,11,13,15,16,34,40], which can act by facilitating wetting [8] and by dissolving into and interacting chemically with the porcelain [10]. True chemical bonding results from electron transfer between the oxygen of the glassy phase of porcelain and an oxidized metal surface. The strongest bonding occurs when there is a chemical equilibrium at the interface relative to the metal oxide and the porcelain at the interface is saturated with the oxide [41]. The common practice of degassing or preoxidizing the metal coping before porcelain application creates surface oxides that improve bonding [3]. The firing time and temperature for optimum oxidation varies from alloy to alloy and is established according to the recommendations of manufacturers. The oxide layer between the metal and ceramic should have an optimum thickness for a strong metal–ceramic interfacial bond. Insufficient or too thick oxide layer can adversely effects bond strength [42]. In the current study, degassing or preoxidizing process of the metal alloys were carried out to promote bond strengths for each metal–ceramic complex as recommended by the manufacturers.

Moffa et al. [28] stated that the presence of nickel or chromium oxide at the ceramoalloy interface could augment bonding by contributing to compressive bonding. Conversely, Sced and McLean [43] concluded that chromium ions of base metal alloys diffuse into porcelain from the oxide interface. They stated that chromium oxide reduces the expansion coefficient of dental porcelain to an unacceptable level. This result is a high degree of residual stress at the bond interface, creating the possibility of spontaneous fracture under clinical use. They demonstrated the effect of chromium oxide on the expansion coefficient of Vita VMK porcelain by graphic illustration. Hammad and Stein [44] reported that the residual stresses reported by Sced and McLean could only have an effect for Vita VMK porcelain. The findings of our investigation with Vita VMK 95 supported those reported in the investigation of Sced and McLean [43].

Gold–platinum alloys are high-noble alloys that may be used for full cast or metal–ceramic applications. They may contain zinc or silver as hardeners and are often multiple-phase alloys. These alloys were initially developed as palladium-free alternatives in the early 1990s [16]. Some side effects of palladium (Pd), such as allergies, were lately found, and the risk of using palladium in dental casting alloys was raised [45]. Also, palladium reacts with hydrogen and results in porous castings [46]. Although several studies [46,47] have focused on the strengthening of Pd-free high gold dental alloys, no study has been found in the literature that reveals clear results related to the bond strength of this type of gold-based alloys bonded to various porcelain systems. Thus, it seems that our study, for the first time, presents information about the bonding strength of Au–Pt–Zn metal alloy to different porcelain systems.

Although it is generally agreed that noble alloys produce more predictable bond results than do base alloys, the results of this investigation showed that most of the porcelain systems bonded to base metal alloys produced greater bond strengths than those bonded to noble alloys. These results are agree with the research results reported by other investigators [28,44,48]. Also, Lubovich and Goodkind [49] studied bond strength of precious, semiprecious and non-precious ceramic-metal alloys with two porcelain systems and demonstrated lower or higher bond strengths for base metal alloys in comparison to gold-based alloys.

While de Melo et al. [17] reported higher or lower shear bond strengths for Co–Cr alloys in comparison to Ni–Cr alloys, our study showed higher flexural bond strength values for Wirobond C (Co–Cr) alloy in comparison to Wiron 99 (Ni–Cr) alloy for all porcelain systems, which is consistent with the results of Sced and McLean [43], Schwarz et al. [50] and Uusalo et al. [51].

The bond strength values obtained in this study are consistent with those of the previous studies in which 3-point bending tests were used [1,14,19,33,52]. With the 3-point bending test, Al Mutawa et al. [1] obtained flexural bond strength of 48 MPa, using Au–Pt–Pd alloy with Vita VMK 68 porcelain system. The mean bond strength value of 48.74 MPa, which was obtained in our study for the Au–Pt–Zn alloy (BioPontoStar) with Vita VMK 95 is consistent with their study.

By using 3-point bending test, Atsü and Berksun [33] found the mean bond strength value of 29.26 MPa between Ni–Cr alloy (Remanium CS) and IPS Classic porcelain system, whereas we obtained 48.14 MPa between Ni–Cr alloy (Wiron 99) and IPS Classic. On the other hand, with the same type of test, Yılmaz and Dinçer et al. [19] reported the mean bond strength value of 44 MPa between Ni–Cr alloy (Remanium CS) and Vita VMK 68 porcelain system, which is different from the one we obtained between Ni–Cr alloy (Wiron 99) and Vita VMK 95, as 33.70 MPa. These results are compatible with the results obtained in the study of de Melo et al. [17] who found different mean bond strength values when the same porcelain used with different brands of Ni–Cr alloys. Comparing our study with other studies may be misleading because of the variations in the mechanical properties of the alloys.

Lubovich and Goodkind [49], who used cylindrical pull-through test, reported that although the difference was not significant, Vita porcelain produced greater bond strength than Ceramco when used with traditional gold-based alloy (SMG III). In our study, considering flexural bond strength of porcelain systems bonded to gold-based alloy (BioPontoStar), the maximum bond strength value was obtained with Ceramco II and there was a significant difference between Ceramco II and Vita VMK 95 porcelain systems. The reason for the incompatibility of the results in the two studies might be the use of gold-based alloys with different compositions.

It is also important to point out that the framework strength does not depend exclusively on the alloy used, but also on its design [53,54]. Sharp and much defined shapes often have very low resistance to fracture [53]. Therefore, alloys to be used in the ceramometal restorations cannot be chosen by clinicians based exclusively on the material's bond strength.

Although the data obtained in our study can be helpful for the selection of the most suitable materials for clinical use, it is

important to highlight that the continuous development of new metal alloys and ceramic systems requires further research to assess the compatibility of the metal–porcelain complexes. Also, longitudinal clinical trials are required to investigate the behavior of these materials in the metal–ceramic restorations under clinical conditions.

5. Conclusions

Within the limits of this study, the following conclusions were drawn:

(1) According to the 3-point bending test results, although statistically significant differences between metal–porcelain systems were found, the bending strength values of all metal–porcelain systems were within the acceptable levels in DIN 13927. From the available data it appears that Finesse, Ceramco II, IPS d-sign, IPS Classic, VMK 95 and Omega 900 porcelains present enough bond strength and can clinically be used with any of the alloys tested in this study.
(2) Ceramco II porcelain system showed the greatest mean bond strength value than the other systems when fused onto BioPontoStar alloy. This difference was statistically significant, except for Omega 900. Ceramco II and Omega 900 were found as the most reliable systems that can be used with BioPontoStar (gold-based) alloy.
(3) Since Omega 900 and IPS Classic porcelain systems demonstrated higher mean bond strength values than the other systems when bonded to Co–Cr alloy and the difference between Omega 900 and IPS Classic was not statistically significant, Omega 900 and IPS Classic are the porcelain systems that are most compatible with Wirobond C (Co–Cr) metal alloy.
(4) The mean bond strength values for Omega 900, Finesse and IPS Classic porcelain systems were higher than the other systems when bonded to Wiron 99 and these differences were statistically significant. Omega 900, Finesse and IPS Classic were found as the most compatible porcelain systems for Wiron 99 (Ni–Cr) metal alloy.

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