Ceramic Pressed to Metal Versus Feldspathic Porcelain Fused to Metal: A Comparative Study of Bond Strength

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Purpose: The aim of this study was to compare the debond/crack initiation strength (D/CIS) of a leucite-based low-fusing ceramic pressed (PC) to metal and feldspathic porcelain (FP) fused to metal. ***Materials and Methods:*** Forty rectangular metal specimens, 20 noble alloy (NA; gold-palladium) and 20 base metal alloy (BA; cobalt-chromium) were fabricated per ISO 9693:1999 standards (25.0 mm × 0.5 mm × 3.0 mm). Ten samples in each group received FP and the remaining 10 received PC. The samples in the PC group underwent wax pattern build-ups and subsequent investing and casting. The ceramic dimensions in all four groups were 8.0 mm × 1.0 mm × 3.0 mm. The final metal-ceramic specimen thickness was 1.5 mm. All specimens were subject to the Schwickerath crack-initiation three-point bending test at a crosshead speed of 1.5 mm/min. Metal-ceramic fracture loads were recorded in Newtons and D/CIS was calculated using the formula: $\tau_b = k \times F_{fail}$. ***Results:*** Mean D/CIS were as follows: BA-FP: 36.11 ± 2.31 MPa, NA-FP: 42.64 ± 1.94 MPa, BA-PC: 37.47 ± 6.02 MPa, and NA-PC: 47.94 ± 3.92 MPa. A 2-way ANOVA revealed no significant difference in D/CIS values between the four groups. A statistically significant difference was noted when comparing the mean D/CIS values obtained between the two metal alloys used (NA: 45.29 MPa and BA: 36.79 MPa). ***Conclusion:*** No differences ($P > .05$) in mean D/CIS were found between the low-fusing ceramic pressed to metal and the FP fused to metal. A higher mean D/CIS ($P > .05$) was found for the NA compared to the BA, with both ceramics tested. *Int J Prosthodont 2009;22:94–100.*

Despite the widespread use of all-ceramic systems today, metal-ceramic restorations are still considered the primary means of restoration due to their superior mechanical strength. The metal substructure in a metal-ceramic restoration is ductile, bends under load, and has the ability to return to its original form.[1] The fracture resistance of the metal, in combination with the esthetic nature of porcelain, has provided dentists with both durable and esthetic restorations.[2]

The bonding of porcelain to dental alloys occurs during porcelain firing, a process known as sintering. It occurs due to four mechanisms: chemical bonding, mechanical interlocking, van der Waals forces, and forces of compression.[3] Once bonded, the underlying metal substructure provides support for the porcelain, thereby increasing the strength of the ceramic and placing its outer surface in compression.[3] The most important of the four mechanisms is the formation of a chemical bond which results in a thermodynamic equilibrium between the metal and the porcelain by the formation of an intermediate oxide layer.[4] The metal-ceramic bond is further enhanced by an actual physical interlocking of the ceramic with the metal. Surface roughness can improve this phenomenon to a certain extent. However, it can also lead to the formation of voids at the interface, which can adversely affect bonding.[5] Van der Waals forces contribute in small part to metal-ceramic bonding via interatomic forces.[5]

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Compressive forces in a metal-ceramic system are the result of a slightly higher coefficient of thermal expansion (CTE) of the metal compared to the veneering porcelain. A difference in the CTE of 1.7 × 10^{-6} °C between the metal and porcelain can result in shear stresses at the interface and lead to an ultimate failure of the metal-ceramic bond.[6] The ideal difference in the CTEs between metal and ceramic should not be greater than 1 × 10^{-6} °C.[6] The melting range, however, should be greater for metal alloys to allow firing and glazing of the porcelain. Melting ranges for dental alloys are typically 170°C to 280°C higher compared to that of porcelain.[6]

Failure of the metal-ceramic bond has been shown to be dependent on many variables, including firing temperatures and surface textures of the alloy systems.[7] In 1977, O'Brien,[8] in his nonspecific cohesive plateau theory, hypothesized that when a metal-ceramic system is loaded, failure occurs at areas where bonding is the weakest, so that if the adhesive bond between the ceramic and metal is sufficient, the failure will be cohesive within the ceramic.

The longevity of the metal-ceramic bond has been shown to be mainly dependent on the formation of metallic oxides and the interdiffusion of ions between the metal and porcelain.[2]

Many types of alloys have been used for metal-ceramic restorations. Those that have proven most reliable are the noble alloys containing primarily gold, palladium, and a small percentage of indium. However, the main disadvantage with these alloys is their high cost and lack of adaptability with different ceramic systems.[5] Carr and Brantley[9] demonstrated that liquid palladium can absorb an excessive amount of gas which then can be released during casting and lead to numerous microporosities.

Base metal alloys have certain desirable properties such as low cost, increased strength and hardness, and greater resistance to distortion, but they sometimes exhibit excessive oxide formation, prove difficult to finish and polish due to their low ductility, and exhibit a greater casting shrinkage.[5] Seed and McLean[10] demonstrated that Ni and Cr oxides in base metal systems decreased the coefficient of expansion of Vita (Vident) porcelain and suggested that this could induce interfacial stresses and result in failure of nonprecious ceramic alloys. Mackert et al[11] postulated that there exists a strong correlation between oxide formation and metal-ceramic bond strength. Rake et al[12] demonstrated high bond strength values in a gold-palladium alloy with an intact oxide layer when compared to a nickel-chromium base metal alloy.

Although traditional feldspathic porcelain has been around for decades and is the primary ceramic of choice for porcelain-fused-to-metal restorations, the newer pressable ceramics provide certain advantages. Pressable glass ceramics exhibit high compressive strengths.[13] They also exhibit higher flexural strength over traditional porcelain. This has been attributed to an increased presence of the uniformly distributed leucite phase.[13]

The lost wax technique of ceramic application used in conjunction with pressable ceramics results in porcelain application, that is simpler and quicker than some of the conventional techniques available and produces acceptable marginal accuracies.[14] This technique also eliminates the need to compensate for the 20% shrinkage seen with traditional porcelain firing.[15]

The recently introduced low-fusing, leucite-based pressable porcelain systems have melting temperatures low enough to match that of commercially available metal frameworks. In addition, the CTE may be adjusted to match a range of metal substructures, allowing the use of these ceramics in traditional metal-ceramic systems.[16]

An abundance of testing systems have been described to study the metal-ceramic bond. Ringle et al[17] described a method to quantify the 'adherent' porcelain on debonded metal-ceramic specimens using silicon x-rays in a scanning electron microscope. In comparing gold alloys with Ni-Cr alloys, he found that more porcelain was retained on the gold alloys compared to the base alloys. Hammad and Talic[18] reviewed the various test designs that were used experimentally to evaluate bond strengths at the porcelain-metal interface. It was concluded that there was no single system that could accurately record bond strength, and that one could only approximate what these values might be. Anusavice et al[19] carried out finite element analyses on the stress distribution at the interface of 11 debond strength tests. He reported that forces of tension are greatest at the terminal areas of the metal-ceramic interface. Papazoglou and Brantley[20] concluded that an accurate test should cause debonding of the ceramic at the interfacial region and not a tensile failure of the ceramic due to bending stresses. They proposed that different testing designs produced mean bond strength values that were not comparable due to different stress patterns.

Although multiple mechanical tests have been used over the last two and a half decades, the more recent Schwickerath crack-initiation three-point bending test, standardized by the ISO (ISO/FDIS 9693:1999),[21] is now considered the gold standard for testing metal-ceramic bond strength.

The purpose of this study was to compare the shear bond strength (debond/crack initiation) of a leucite-based low-fusing ceramic pressed to metal and feldspathic porcelain fused to metal.

Table 1 Metals Used in the Study

Metal/ composition	Elastic modulus (MPa)	Vickers hardness	Tensile strength (MPa)	Elongation (%)	Melting range (°C)	Casting temp (°C)	CTE ($\times 10^{-6}$°C)
Argedent 65SF (Noble) Au 65 Pd 26 In 8.65	120	250	690	15	1141–1255	1400	14.4
Gialloy CB (Base) Co 61 Cr 28 Si 1.7 W 8.5 Fe < 0.5 Mn 0.25	190	285	840	10	1320–1420	910–940	14.1

Table 2 Porcelains Used in the Study

Ceramic	Fusion temp (°C)	Flexural strength (MPa)	CTE ($\times 10^{-6}$°C)	Solubility (mg/cm^2)
Creation (Feldspathic)	920	84	13.3	12
Authentic (Pressed)	940	148	17.7	≤ 30

Table 3 Differences in the Mean Debond Strength Values when Comparing the 2 Metals Used in the Study-Argedent and Gialloy

NA_BA	Mean	Standard error	95% Confidence Interval Lower bound	Upper bound
NA	45.29	2.7	39.6	50.9
BA	36.79	2.7	31.1	42.4

Dependent variable: Strength.

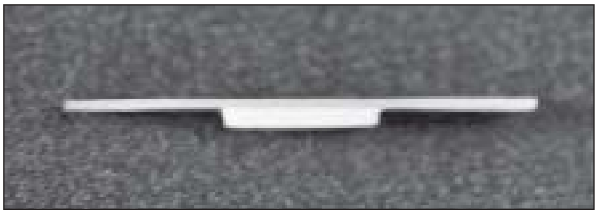

Fig 1 Metal sample following porcelain application.

Materials and Methods

Forty metal specimens were fabricated for the study per ISO standards (ISO 9693:1999): 20 noble alloy (NA; Argedent 65SF) and 20 base metal alloy (BA; Gialloy CB) (Table 1).

Sheets of 24-gauge wax (Kerr/Sybron) were cut into strips 0.6 mm × 26 mm × 3.5 mm in dimension and then cast to obtain the rectangular metal specimens. The wax patterns were sprued and invested in a phosphate-bonded investment (Finesse, Ceramco). Once the investment had set, the wax patterns were placed in a burnout oven at room temperature (Accu-Therm II 250, Heraeus Kulzer, Jelenko). They were then heated gradually to 800°C to ensure complete wax elimination. Following burnout, the specimens were cast using a centrifugal casting machine (74 Exac-U-Cast). They were then divested and sandblasted (Micro-etcher, Model ERC, Danville Engineering) for 15 seconds with 50-µm aluminum oxide particles at 60 psi. The metal specimens were cleaned in an ultrasonic distilled water bath for 30 minutes.

Each metal specimen was shaped by hand to obtain dimensions of 25 mm in length and 3 mm in width using a polisher (Phoenix Beta, Buehler). In order to obtain a thickness of 0.5 mm, the metal specimens were affixed to the polisher wheel with cyanoacrylate cement (Borden Elmer) and subsequently ground. The samples were removed from the polishing wheel with acetone. A digital caliper (Mitutyo series no. 500) was used to record the final dimensions. Prior to ceramic application, the specimens were sandblasted with 50-µm aluminum oxide particles at 60 psi for 15 seconds and cleaned in an ultrasonic distilled water bath for 30 minutes.

Ten samples were randomly chosen from each group (NA and BA) to receive feldspathic porcelain application (Table 2). Two layers of opaque (Creapast, Jensen) were applied to the metal specimen and fired individually under a vacuum in a calibrated oven (Commodore 100 UFF, Jelenko) to a temperature of 980°C. Dentin or body porcelain (Creation, Jensen) was then vibrated and condensed onto the surface of the metal specimen and fired under a vacuum to a temperature of 920°C to a dimension of 8 mm × 1 mm × 3 mm. Similarly, two layers of opaque were applied and fired individually on the remaining samples from each of the two groups. They then had a pressable ceramic wax applied to a thickness of 1 mm.

The metal-wax specimens were subsequently sprued and invested in a phosphate-bonded investment. The wax was then eliminated at 850°C (Accu-Therm II 250). Pressable ceramic ingots (Table 2) of a low-fusing leucite-based glass ceramic (Authentic, Ceramay) were then pressed onto the metal specimens at 940°C. The metal-ceramic specimens were then divested and sandblasted for 15 seconds with 50-µm aluminum oxide particles at 60 psi.

The ceramic specimens in all four groups were shaped in the polisher (Phoenix Beta) to dimensions of 8 mm × 1 mm × 3 mm.

The metal-ceramic specimens (Fig 1) were then subjected to a three-point bending test (ISO/FDIS 9693:1999) on an Instron testing machine (Model no. 5566, Instron). The testing apparatus consisted of two metal supports 20 mm apart. The specimen was placed equidistant from the metal supports and with the testing surface away from the direction of the applied load. Force was applied at the center of each sample via a rod 2 mm in diameter (Small Parts) at a rate of 1.5 mm/min. Failure of the bond or debonding was indicated by a sharp drop on the load-versus-extension graph.

Metal-ceramic fracture loads were recorded in Newtons. Debond strength was calculated using the formula:

$$\tau_b = k \times F_{fail}$$

where τ_b = debond/crack initiation strength in MPa; k = constant, which is dependant on the thickness of the metal specimen (d_M) and its elastic modulus (E_M); F_{fail} = fracture load recorded just before debonding of the metal-ceramic specimen.

One completely debonded metal sample from each group was examined under the scanning electron microscope (Cambridge Stereoscan 250), at magnifications of 50× and 500×. Surface compositions were analyzed with an energy dispersive x-ray spectrometer (Kevex) at an accelerating voltage of 20 keV.

Four randomly selected samples, which were not debonded, were examined cross-sectionally at the interface of metal and porcelain at 50×, 200×, and 500× magnifications. The debond strength values from the four groups were statistically analyzed with a two-way ANOVA.

Results

The BA with feldspathic porcelain group exhibited a mean debond strength of 36.11 ± 2.31 MPa while the NA with feldspathic porcelain group demonstrated a mean debond strength of 42.64 ± 1.94 MPa. The BA with pressed ceramic group exhibited a mean debond strength of 37.47 ± 6.02 MPa and the NA alloy with pressed ceramic group exhibited a mean debond strength of 47.94 ± 3.92 MPa (Fig 2).

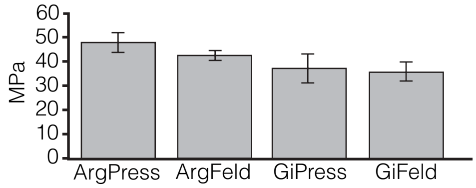

Fig 2 Mean debond/crack initiation strengths of the four groups.

A two-way ANOVA ($P > .05$) was used to compare the mean debond strengths of the four groups and the effects of the two variables (type of metal and porcelain). Results of the ANOVA showed no statistically significant difference in mean bond strengths between the two porcelain groups as well as between the porcelains and metals. However, a statistically significant difference was noted when comparing the mean debond strength values obtained between the two metal alloys used, Argedent 65SF (NA) and Gialloy (BA), with the NA exhibiting higher values (45.29 MPa) when compared to the BA (36.79 MPa) (Table 3).

No significant differences in mean debond strength values were seen when comparing the two types of porcelain-feldspathic and pressed ceramic.

Scanning electron microscopy of the non-debonded specimens showed evidence of crack initiation (Figs 3 and 4) and porosities (Fig 5) at the terminal areas of the porcelain-metal interface.

No apparent differences in the debonded surfaces of the four groups were observed (Figs 6a, 6b, 7a, and 7b), but the NA–pressed ceramic sample (Fig 7a) examined did seem to exhibit more porosities.

Examination of the terminal ends of the metal-porcelain interface in all samples at 200× demonstrated that the failure was initially cohesive through the ceramic, as seen in Figs 8 and 9, which show the initiation of a crack in the opaque layer.

Energy dispersive x-ray analysis at an electron voltage of 20 kV revealed the presence of elements native to each alloy, such as gold and palladium in the NA samples and cobalt and chromium in the BA samples. Those elements found in porcelain, such as calcium, aluminum, silica, and potassium, were also noted.

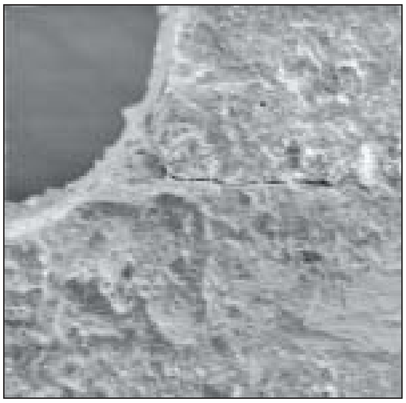

Fig 3 Secondary electron image of the initiation and propagation of a crack of a NA–feldspathic porcelain sample; magnification ×200.

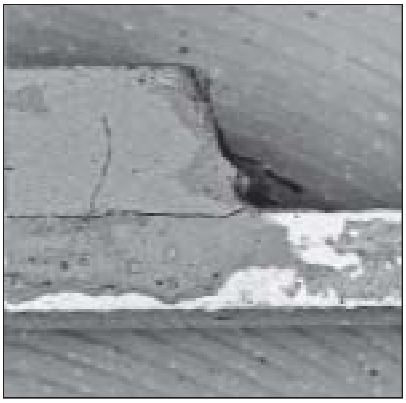

Fig 4 Initiation and crack propagation at the terminal end of a BA–pressed ceramic porcelain sample; magnification ×50.

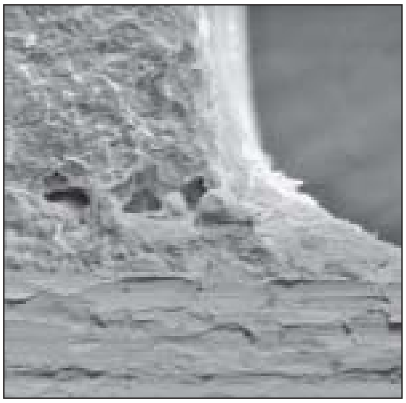

Fig 5 Presence of voids in the porcelain of a non-debonded NA–feldspathic porcelain sample; magnification ×200.

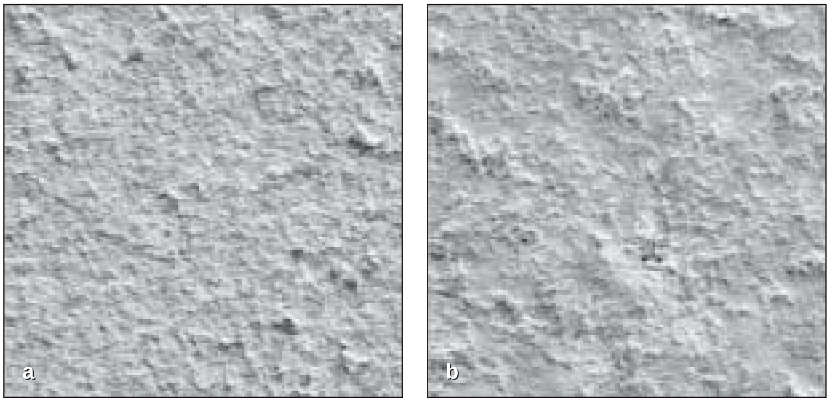

Fig 6 An area of the interface in a debonded metal-ceramic specimen from **(a)** the NA–feldspathic porcelain group and **(b)** the BA–feldspathic porcelain group; magnification ×500.

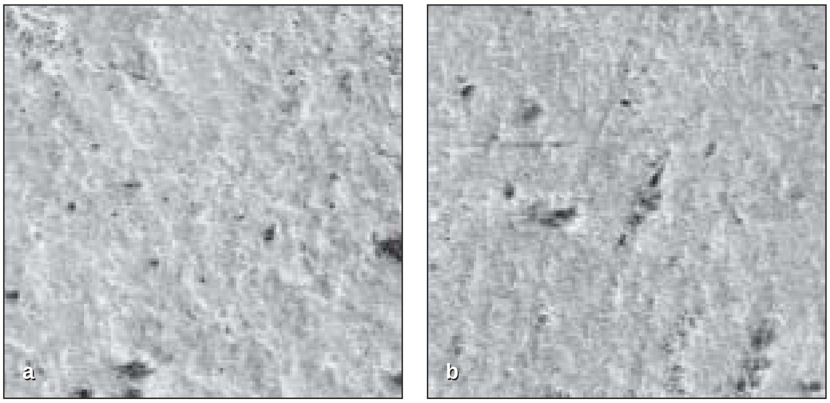

Fig 7 An area of the interface of a debonded metal-ceramic specimen from **(a)** the NA–pressed ceramic group and **(b)** the BA–pressed ceramic group; magnification ×500.

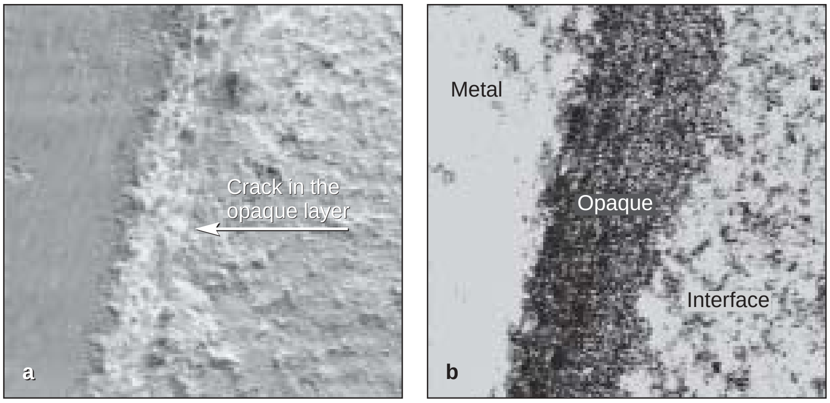

Fig 8 The metal-ceramic interface at the terminal point in a sample from the BA–feldspathic ceramic group at ×200. **(a)** Secondary electron image showing a crack in the opaque layer at the terminal end of the specimen. **(b)** Backscattered electron image distinguishing the metal, opaque layer, and the interface.

Discussion

The results of this study demonstrate no statistically significant differences in mean debond/crack initiation strength (D/CIS) values between the leucite-based low-fusing ceramic pressed to metal and feldspathic porcelain fused to metal. The ISO requirement that at least four test specimens exhibit mean bond strengths (debonding/crack-initiation strength) of 25 MPa was met by samples in all four groups.

Debonding of the metal-ceramic specimens in this study exhibited a pattern of progression from one end of the sample to the other. As discussed by Anusavice et al,[19] forces of tension are greatest at the terminal areas of the metal-ceramic interface. This phenomenon is consistent with findings in this study, where all samples observed under the SEM demonstrated a cohesive-type failure at both terminal ends of the metal-ceramic interface and a 'mixed mode' failure throughout the rest of the sample in areas of greater stress concentration.

Ringle et al[17] reported a method to measure adherent porcelain on debonded specimens using silicon x-rays. Measurement of the percentage of cohesive failure at the interface of a debonded specimen could provide a better glimpse into the nature of the bond-adhesive versus cohesive.

The 2-way ANOVA test demonstrated a significant difference in bond strengths between the NA and BA, regardless of type of porcelain. D/CIS is indirectly related to a metal's elastic modulus (based on the value of constant, K). This is evident in our results where the Gialloy, with a higher elastic modulus, exhibited lower debond strength values with both types of porcelain.

Another reason for this difference could be the excessive formation of oxides, sometimes seen at the metal-ceramic interface of base alloys, resulting in weak chemical bonds between base metals and ceramics, as described by Shillingburg et al.[6] On the same note, Rake et al[12] demonstrated high bond strength values in a gold-palladium alloy with an intact oxide layer when compared to a nickel-chromium base metal alloy.

There exists a strong correlation between oxide formation and metal-ceramic bond strength. In their oxide layer theory, Mackert et al[11] explain that not only must the oxide layer be present at the porcelain-metal interface, but it should also be adherent to the metal. Gold has been shown to form unstable oxide layers,[22] which are not conducive to bonding. It has been hypothesized that hardening ingredients such as tin and indium found in gold alloy precipitate at grain boundaries and play a crucial part in establishing the metal-ceramic bond.[22,23]

Ni and Cr oxides have been shown to decrease the coefficient of expansion of Vita (Vident) porcelain in nonprecious ceramic-alloy systems.[10] The effect of chromium oxide in the BA on the porcelains used in this study is unknown.

One of the two NA (gold-palladium alloy) specimens observed under the SEM exhibited numerous porosities on its surface. However, the clinical significance of this observation is unknown. Carr et al[9] demonstrated that liquid palladium could absorb gases during the casting process and can cause porosities in the casting. An examination of the other NA samples used in this study would demonstrate if this was common to all NA specimens.

A larger standard deviation in mean debond strength values was observed with the samples in the pressed ceramic group. The samples in this group were subject to additional steps of divestment and sprue removal. It is difficult to ascertain the exact effect these procedures had on the debond strength values. Upon return of the pressed ceramic specimens after porcelain application, it was observed that the opaque layer was applied along the entire length of the metal sample. The firing of two opaque layers does not significantly contribute to a change in the thickness of the metal sample, given that the thickness of the opaque is usually in the range of tenths of a mm, so one can postulate that the extension of the opaque layer along the entire length of the sample did not contribute to the variation in the values.

The ideal mismatch between metal and ceramic is well documented but is based on the techniques of baking porcelain to metal. While it is easy to assume that with pressed ceramics CTE mismatch of porcelain to metal would be the same as that of conventional porcelain, to our knowledge, no research has been published on that issue. Usually CTE differences of 1.7×10^{-6}°C or greater between metals and porcelains are known to result in shear stresses at the interface, which can lead to an ultimate failure of the metal-ceramic bond.[6]

Only the NA–feldspathic porcelain and BA–feldspathic porcelain samples in this study exhibited acceptable differences in CTEs. The CTE of the pressed ceramic was greater than both metals used in the study. This could be attributed to the presence of leucite crystals in the pressed ceramic, which has been shown to increase the CTE of porcelain.[24] In this study, there was a mismatch of the CTEs of both metals with the pressed ceramic, but instead of exhibiting lower bond strength values, these groups exhibited marginally higher values.

Ideally, the metal-ceramic bond should be stronger than the cohesive strength of the porcelain unit (opaque + body porcelain). Therefore, cohesive fracture within any part of the porcelain unit would indicate a good metal-ceramic bond. In this study, the debonding strength values in all four groups met the

ISO standard of 25 MPa, indicating a good bond, but not revealing a superiority of one group over another. It is acknowledged that once a compelling bond is formed at the metal-ceramic interface and cohesive failure occurs, the interface of the opaque to body porcelain becomes suspect. Indeed, clinically, this is where most debonded metal-ceramic restorations fail.

This study employed the Schwickerath crack initiation three-point bending test standardized by the ISO. In order to measure true metal-ceramic adherence, or force to failure, the test employed should cause debonding of the ceramic layer at the interfacial region, and not tensile failure of the ceramic as a result of bending stresses. Given the differences in CTEs and the introduction of residual interfacial surface tensions, debond strength values can only be approximated.[20]

The data from this study indicate that there might be potential benefits by combining traditional dental casting alloys with the newer, improved pressed ceramics. However, clinical trials are needed to determine their reliability.

Conclusions

The results of this study demonstrated:

- No differences ($P > .05$) in mean debond strength values between the leucite based low-fusing ceramic pressed to metal and the feldspathic porcelain fused to metal.
- A higher mean debond strength ($P > .05$) for the noble alloy compared to the base alloy, with both ceramics tested.

Acknowledgment

This study was funded by Zubler Geratebau GmbH of Ulm-Jungingen, Germany.

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