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Improving the functional design of dental restorations by adding a composite interlayer in the multilayer system: multi-aspect analysis

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Abstract

The performance of dental restorations has been a concern of dentists and engineers. One of the topics that have concentrated most effort has been the study of the properties of the interface between the veneering porcelain to metallic or ceramic substrates, namely on the improvement of the adhesion between the two materials and its behaviour under oral conditions. This paper discusses the benefits of placing a composite interlayer (50% metal + 50% ceramic, vol.%) at interface between metal and ceramic in a dental restoration. The discussion covers the following aspects: performance of this system under thermomechanical fatigue conditions, thermal and mechanical properties of the composite interlayer, thermal residual stresses arising after porcelain sintering and technical feasibility on a prosthetic laboratory.

Keywords: Metal-ceramic restoration; composite; mechanical properties; thermal properties; thermal residual stresses; thermal cycling; bond strength.

1. Introduction

Teeth are often lost due to disease or trauma that can affect mastication and aesthetics. The metal-ceramic restorations are still the most used prosthetics solution for missing teeth. A metal-ceramic dental prosthesis consists on a strong and stiff metallic substructure that is veneered by aesthetic porcelain that mimics the teeth appearance. These are considered reliable prostheses although the clinical failure due to fracture and exfoliation of the porcelain are reported as being up to 10% in periods of 10 years [1]. Achieving a good bond between the metal and ceramic can result in the production of more reliable restorations with lower failure rates. The following treatments have shown good results in the bond strength improvement between metal and ceramic: the addition of easy-oxide forming elements to noble alloys [2,3]; the coating of reactive metals surfaces (e.g. titanium alloys; CoCrMo alloys) with oxide-controlling elements [4-6]; the use of bonding agents [7,8]; pressure aided techniques [9,10], among others. Nevertheless, a significant increase in bond strength was demonstrated when a metal-ceramic composite was used as interlayer between the metallic substructure and the ceramic veneer [11-15]. The overall benefits of the employment of such composites are presented and discussed in this paper.

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2. Performance under thermomechanical fatigue conditions

Previous studies conducted by the same authors of this paper evaluated the presence of a composite interlayer on the bond strength of porcelain to metallic substrates in load to failure tests [11,12] and significant improvements in adhesion were observed relative to conventional metal-ceramic sharp transition interface configuration. Specimens with composite interlayer also showed better performance under thermomechanical fatigue tests [13]. In this study two interface designs were analyzed: A) a conventional sharp transition between metal and porcelain, and B) a composite interlayer (50%metal + 50%porcelain, vol.%) placed at the interface between metal and porcelain (Figure 1). Specimens with a sharp transition were produced by the conventional porcelain-fused-to-metal technique. The specimens having the composite interlayer were obtained by hot pressing, an equivalent process to porcelain injection used in dental prosthetic laboratories. Specimens were manufactured and standardized in cylindrical format and then submitted to thermal (3000, 6000 and 12000 cycles; between 5ºC and 60ºC; dwell time: 30s) and mechanical (25000, 50000 and 100000 cycles under a load of 50N; 1.6Hz) cycling, simulating the degradation at intra-oral conditions. The shear test was used to assess bond strength between metal and ceramic. The shear bond strength tests were carried out at room temperature and performed in a universal testing machine (Instron 8874, MA, USA), with a load cell of 25 kN capacity and under a crosshead speed of 0.5mm/s. Tests were performed in a custom-made stainless steel apparatus similar to that described by Henriques et al. [15].

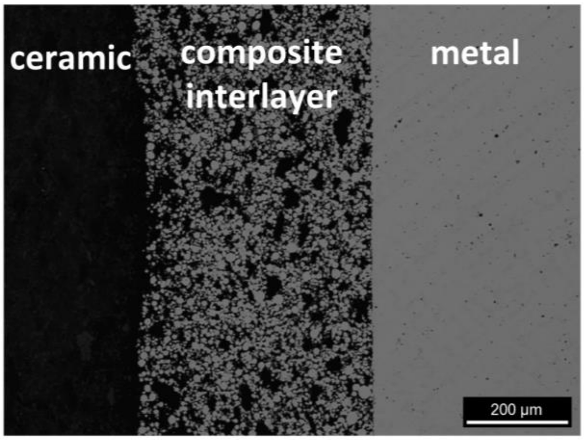

Fig. 1. Micrograph of the composite interlayer (at the center) between the metal (right) and porcelain (left).

The apparatus consisted in two sliding parts A and B, each one with a hole perfectly aligned to the other. After aligning the holes, the specimens were inserted and loaded at the interface until fracture. The shear bond strength (MPa) was calculated by dividing the highest recorded load (N) by the cross sectional area of resistant porcelain (mm^2).

The specimens with the composite interlayer performed significantly better under thermomechanical fatigue conditions, exhibiting significantly higher bond strength values after fatigue tests than those revealed by specimens with sharp transition (Figure 2). The improvement in bond strength exhibited by the former specimens relative to conventional sharp transition ones, before thermomechanical fatigue tests, was in excess of 130%. This value rose to 240% after the fatigue tests. The bond strength loss after thermomechanical fatigue tests was 11% for specimens with the composite interlayer and 43% for specimens with the conventional sharp transition.

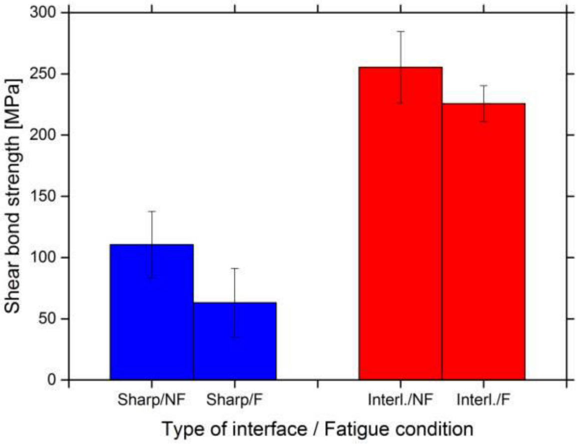

Fig. 2. Shear bond strength results of the two types of metal-ceramic interface designs (Sharp – sharp transition between metal and ceramic; Interl. – composite interlayer between metal and ceramic) and fatigue conditions (NF – Non submitted to fatigue conditions; F – submitted to fatigue conditions). Adapted from Henriques et al., 2012 [13])

The bond strength improvement mechanisms were explained by the bridging effects resultant from the bonds between the metallic particles and the metallic substrate and also between the metallic particles themselves [13,14]. The higher fracture toughness of the composite interlayer relative to the monolithic porcelain was also considered to be important.

Unlike conventional sharp transition specimens, where cracks propagated freely throughout the porcelain and the interface, specimens with the composite interlayer showed crack retention features provided by the metallic particles of the interlayer, which acted as cracks stoppers [14]. They retarded the crack propagation and thus the degradation of the interface.

3. Thermal and mechanical properties of the composite interlayer

The thermal and mechanical properties of several metal-ceramic composites developed for dental restorations have also been evaluated [14]. The microstructure of the composite with the volume content of 50% metal and 50% porcelain is shown in Figure 3.

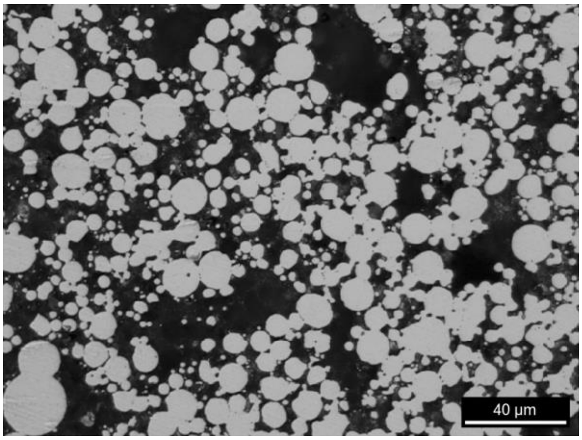

Fig. 3. Micrograph of the composite interlayer containing 50%metal + 50%ceramic.

It shows a well-distributed metallic phase (CoCrMo alloy particles) within a ceramic phase (porcelain). The thermal and mechanical properties of this composite, as compared to the metal and porcelain monolithic materials, are presented in Table 1.

Table 1. Mechanical and thermal properties of the composite interlayer (50%metal+50ceramic) and the monolithic materials (metal and porcelain). Adapted from Henriques et al., 2014 [14]

	CTE [1/10^{-6}]	Hardness [HV1]	E [GPa]	3-point-bending tests TRS [MPa]
Porcelain	8.6	596±8	52	57
Interlayer	11.3	498	120	301
CoCrMo alloy	11.0	513±14	220	2616

*Properties estimated from the data presented in Henriques et al., 2014 [14].
CTE – Coefficient of Thermal Expansion
E – Young's Modulus
TRS – Transverse Rupture Strength

Results show an improvement of elastic and inelastic properties of the composite relative to those of the monolithic porcelain. Despite it is not shown here, the toughness was gets also significantly improved. The properties displayed by the composite, which are intermediate between those of porcelain and metal, allow a gradation in properties of the dental restoration. This gradation is considered to positively impact the clinical performance of the restoration due to a better distribution of stresses when the restoration is loaded.

4. Thermal residual stresses

An analysis of the thermal residual stresses arising on a metal-ceramic crown restoration, after cooling from porcelain sintering, was performed for two types of interface configurations: A) sharp transition between metal and ceramic, and B) composite interlayer (50%metal + 50%ceramic) at the interface between metal and porcelain (Figure 4). A 3D molar tooth model was used and for simplicity reasons the 3D computational model of the crow was sectioned to a 2D-axisymmetric model (Figure 4).

The simulations were conducted using the commercial finite element software COMSOL Multiphysics 4.3a (Comsol Inc, Los Angeles, USA) adapting triangular elements (A- 794 elements; B – 1071 elements) for the composite interlayer. The computational procedure consisted in cooling the model from a temperature of 500ºC to 100ºC, during 1000 s in increments of 100 s, i.e. with a constant cooling rate of 0.25 K/s. The models were considered bonded at the interfaces.

The maximum principal stresses at the interfacial region were taken for each model after the cooling time elapsed. The convergence analysis was performed in order to examine the sensitivity of the results to the size of the mesh.

The thermal residual stresses are shown in Figure 5. The results show clear differences in the stress distribution and magnitude of principal maximum stresses arising in the crown with the composite interlayer when compared to the conventional sharp transition configuration. The maximum residual stresses found in the former crown interface design was146MPa while those found in conventional crown were 180MPa, thus reducing the tensile stresses by 19%. The plot of maximum principal stresses revealed tensile stresses occurring in the metallic substructure and compressive stresses occurring in the porcelain veneering, for the two crown designs.

The peak tensile stress was found at the interface at the metallic substrate side. Zhang et al. (2010) [16] reported similar stress distribution for zirconia and alumina substrates.

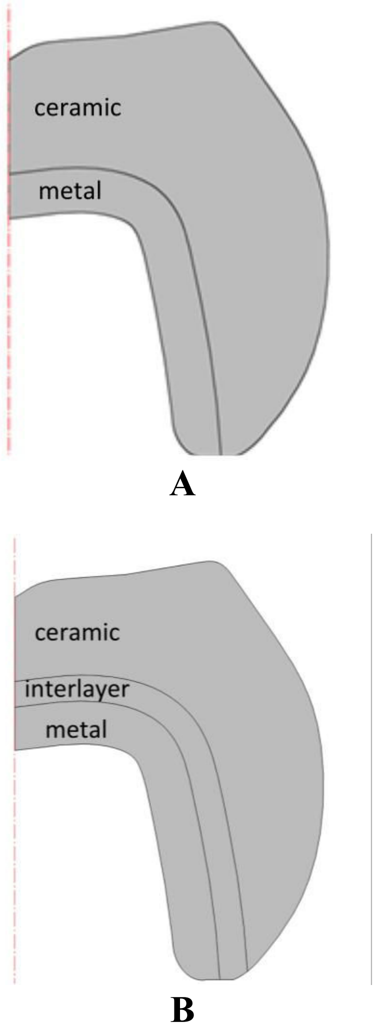

Fig. 4. 2D-axisymmetric model of the metal-ceramic crown with two different interface configurations: A) Sharp transition; B) Composite interlayer at the interface between metal and ceramic.

5. Technical feasibility

Figure 6 shows a real metal-ceramic crown produced with a composite interlayer at the interface between metal and ceramic. The production of this dental crown was proved to be technically feasible using regular procedures and equipment yet found in a prosthetic laboratory. This crown was produced using a commercial porcelain injection equipment (Ivoclar®; IPS Line® PoM – Press on Metal). The composite interlayer comprised a mixture of 50% metal (CoCrMo alloy powder) and 50% porcelain (Ceramco3 Opaque powder) (%vol.). The powder was mixed with water (mixing ratio of 2:1, in weight) and applied with a brush to the metal coping. The coping was then placed in the furnace for the composite sintering according to the porcelain firing cycle. Afterwards, two opaque layers were applied over the sintered composite interlayer.

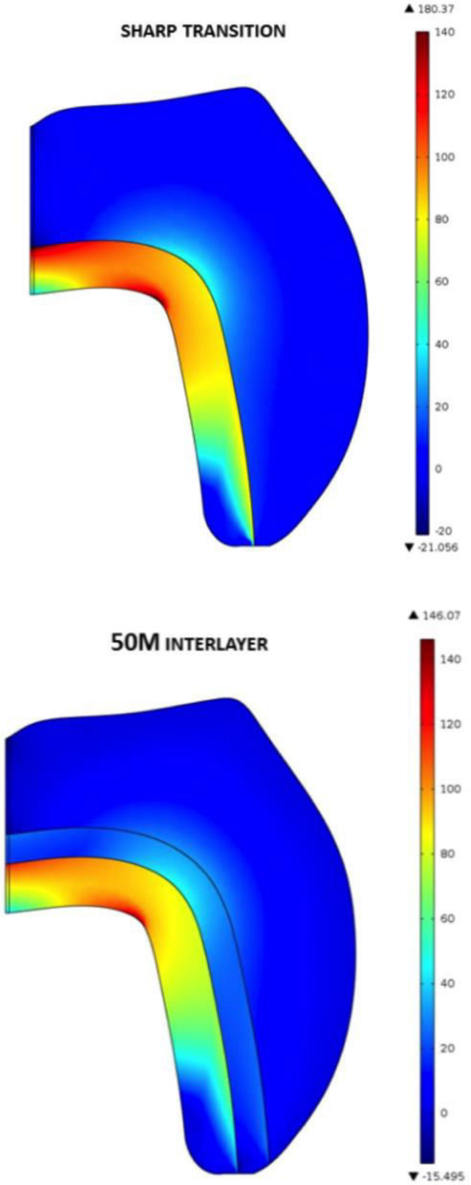

Fig. 5. Plot of the thermal residual stresses (maximum principle stresses) arising in a dental crown after cooling from the porcelain sintering temperature for two types of interface configurations: A) sharp transition between metal and ceramic; B) composite interlayer at the interface between metal and ceramic.

In Figure 6 is also shown the cross section of the crown. The metal-interlayer-ceramic region was analyzed by optical microscopy in several locations. It was observed a good adhesion between the interlayer and the metal, and between the interlayer and the porcelain. The interlayer exhibited residual porosity though that can be avoided if less liquid is used in the preparation of the metal/ceramic composite mixture. A variation of the thickness of the interlayer is also visible, which might be related to the type of method used for application of the composite (brush).

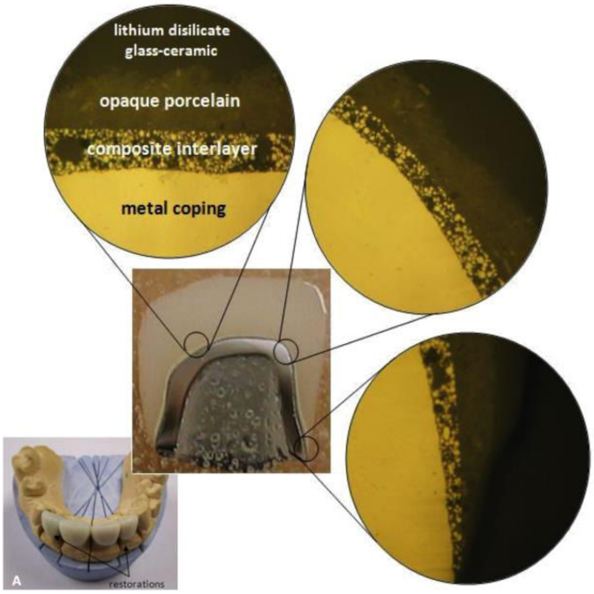

Fig. 6. Details of a metal-ceramic dental crown (anterior teeth) with a composite interlayer (50%metal+50%ceramic) at the interface.

6. Conclusions

The use of a composite interlayer proved to have several benefits over the traditional sharp transition configuration, at several levels: significant improvement of the metal-ceramic bond strength relative to the sharp transition (i.e. by 130% and 240%, before and after thermomechanical fatigue tests, respectively); improved performance under thermomechanical fatigue conditions (11% and 40% of bond strength loss for sharp transition configuration and composite interlayer configuration, respectively); reduction of the magnitude of the thermal residual stresses (by 19%) arising after porcelain firing procedure.

The production of metal-ceramic prostheses with a composite interlayer at the metal-ceramic interface was shown to be feasible with standard prosthetic laboratory equipment.

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References

[1] T.E. Donovan, EJJr Swift, *J. Comp.* **1**, 4-6 (2009).

[2] J.A. Hautaniemi, *J. Mater. Sci: Mater. Med.* **6**, 46-50 (1995).

[3] B. Henriques, D. Soares, F. Silva, *Mater. Sci. Eng. C.* **32**, 8 2374-2380 (2012).

[4] I. Özcan, H. Uysal. *Dent. Mater.* **21,** 773–779 (2005).

[5] J. Bieniaś, B. Surowska, A. Stoch, H. Matraszek, M. Walczak. *Dent. Mater.* **25**, 1128–1135 (2009).

[6] S.E. Elsaka, I.M. Hamouda, Y.A. Elewady, O.B. Abouelatta, M.V. Swain. *J. Dent.* **38**, 8, 648-654 (2010).

[7] Z.D. Yesil, S. Karaoglanoglu, M.S. Akyıl, Seven N. *Inter. J. Adhesion & Adhesives* **29**, 32–35 (2009).

[8] W.C. Wagner, K. Asgar, W.C. Bigelow, R.A. Flinn. *J. Biomed. Mater. Res.* **27**, 531-537 (1993).

[9] B. Henriques, D. Soares, F. Silva. *Mater Sci Eng C* **33**, 1, 557-563 (2013).

[10] B. Henriques, D. Soares, F. Silva, *J. Mech. Behav. Biomed. Mater.* **4**, 8, 1718-26 (2011).

[11] B. Henriques, D. Soares, F. Silva, *Mater Sci Eng A* **528**, 1415-1420 (2011).

[12] B. Henriques, M. Gasik, D. Soares, F. Silva, *J. Mech. Behav. Biomed. Mater.* **13**, 206-214 (2012).

[13] B. Henriques, S. Felix, D. Soares, F. Silva, *J. Mech. Behav. Biomed. Mater.* **13**, 94-205 (2012).

[14] B. Henriques, M. Gasik, J. Souza, D. Soares, R.M. Nascimento, F.S. Silva, *J. Mech. Behav. Biomed. Mater.* **30**, 103 – 110 (2014).

[15] B. Henriques, D. Soares, F.S. Silva. Optimization of bond strength between gold alloy and porcelain through a composite interlayer obtained by powder metallurgy. *Mater. Sci. Eng. A.* 528, 1415-1420 (2011).

[16] Z. Zhang, S. Zhou, Q. Li, W. Li, M. Swain, *Adv. Mater. Res.* **97**, 101, 2241-2244 (2010).