

SHEAR BOND STRENGTH AND FAILURE MODE BETWEEN VENEERING CERAMIC AND METAL CORES AFTER MULTIPLE FIRING CYCLES

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ABSTRACT

Purpose: To investigate the effect of multiple firing cycles on shear bond strength and failure mode of porcelain fused to metal.

Materials and method: Sixty porcelain fused to metal discs were divided into four groups according to number of firing cycles subjected to; group A; one firing cycle, group B; two firing cycles, group C; three firing cycles and group D; four firing cycles to sinter the porcelain. All the specimens were thermocycled for 300 cycles then collected, labeled and stored in distilled water for 48 hours before testing. Shearing test was done by compressive load applied using a mono-bevelled chisel shaped metallic rod attached to the upper movable compartment of testing machine traveling at cross-head speed of 0.5 mm/ min. Fractured specimens were ultrasonically cleaned, carefully checked under digital microscope (Dino-Lite, 241 Taiwan). All failures mode were analyzed.

Results: The highest mean value was observed in group A (21.62 MPa) and the lowest mean value was observed for group B (19.29 MPa). Statistical analysis revealed no significant difference between groups ($P=0.644$). Statistical analysis among groups showed no significant differences either.

Conclusion: Repeated firing cycles up to four cycles had no significant effect on shear bond strength of porcelain fused to metal. Regarding failure mode; all samples had mixed (cohesive adhesive) failure.

KEYWORDS: Shear bond strength, Firing cycles, PFM, MCR, Porcelain and Metal.

INTRODUCTION

Metal ceramic restorations (MCR) has been considered the golden standard for prosthetic dentistry for the past 40 years.⁽¹⁾ This maybe due to their optimum mechanical properties and

fair esthetic qualities, alongside with a clinically satisfactory marginal and internal adaptation.⁽²⁻⁸⁾ Its bilayered configuration made it to be considered as hybrid restoration, composed of two materials; metal coping and ceramic veneer.

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In spite of the increase in the use of all-ceramic restorations (ACR), MCR continued to be used due to their low clinical failure (5-year cumulative failure of 4.4%), compared to 6.7% if all ceramic restorations.^(9,10) Moreover MCRs are still indicated where ACR can not function; as in case of increased occlusal load, limited inter-arch space (which limits the thickness of the connectors)⁽¹¹⁾, increased span length and full-arch Prosthesis.

Although manufacturers routinely advertise all-ceramic systems as a viable option for anterior and posterior Fixed Partial Dentures (FPDs). True, there are few clinical studies to support these claims.^(12,13) Karlsson⁽¹⁴⁾ revealed a 93% success rate in a 10-year period, while Palmqvist and Swartz⁽¹⁵⁾ reported a 79% success rate over an 18- 23-year period. In a review of FPDs failures on the past 50 years, Goodacre, et al.⁽¹⁶⁾ found that the porcelain fracture was the main factor for failure. The decrease in FPD survival rate after 10 years may be a result of material fatigue⁽¹⁷⁻²⁰⁾ and/or a combination of biologic and biomechanical factors^(21,22).

Veneer chipping or fracture is one of the most disagreeable esthetic failure and may be attributed to many factors; increased thickness of veneer, sharp metal angles^(23,24), high occlusal contacts, bending of FPD.

To achieve perfected contour, color, and esthetics qualities, multiple firing cycles may be necessary for the construction of MCRs, especially when using the standard layering technique to reach optimum esthetics.

The adhesion mechanism between metal and porcelain is believed to be the micro-mechanical bond, compatible coefficient of thermal expansion (CTE) match, van der Waals force, and mainly the suitable oxidation of metal and inter-diffusion of ions between the metal and porcelain.⁽²⁵⁾ Data presented in literature has shown the bond strength of ceramic to metal substrates to be in the range of 54 - 71 MPa⁽²⁶⁾, and a sufficient bond for metal-ceramic has been accepted when the fracture stress is greater than 25 MPa.^(27,28)

Residual stresses can likely accumulate during the heating and cooling firing procedures, mainly because of the cooling rate and the CTE mismatch between core and veneer materials. When additional stresses are applied to the restoration, the probability of failure due to fatigue crack propagation might increase, explaining the veneer chipping or fracture. Till now, the effect of multiple firing cycles on the porcelain-metal adhesion remains unclear. The hypothesis of this study is that; the increase in firing cycles might decrease SBS between metal core and veneer.

MATERIALS AND METHOD

Preparation of metal core discs

A 3 mm thickness X 10 mm diameter disc was drawn on AutoCad (AutoDesk, San Rafael, CA, USA) and exported to Micro SLA 3D printer (ProJet 1200, 3D systems, South Carolina, USA). A castable liquid plastic cartridge (VisiJet FTX Green UV Curable Plastic, 3D systems, South Carolina, USA) was inserted into the 3D printer. Micro-SLA is an additive manufacturing technology in which a thin layer of resin is contained in a build tray. The build platform lowers, transferring the resin to the build platform, and then the layer is cured by a UV projector. This process is repeated, building the part layer by layer until the model is finished. Sixty discs were manufactured having the same dimension using stereolithography technology. Support material were cut off the discs and then dipped in isopropanol alcohol solution for cleaning printed discs. (I.P.A, 3D systems, South Carolina, USA) (Fig. 1)

Disc patterns were sprued and invested to be cast into Co-Cr discs (Remanium Star, Dentaaurum, Germany). Discs were air particle abraded using 100 µm Al₂O₃ at 80 psi (Fig.2 A&B) and then were cleaned using ultrasonic water bath (BioSonic, UC 125, Coltène/Whaledent AG, Switzerland).



Fig. (1) 3D printed disc patterns.

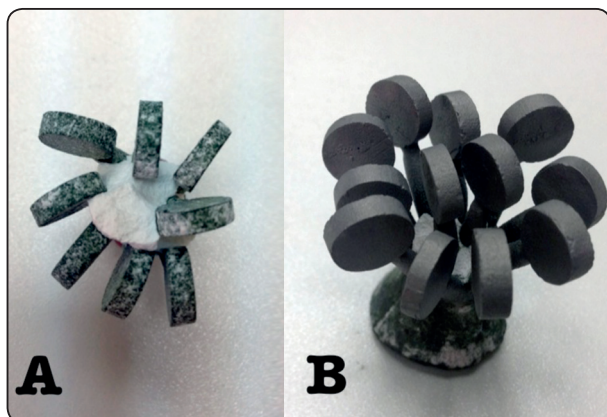


Fig. (2) A: metal discs after casting. B: metal discs after Air Particle Abrasion.

Metal discs were finished using heatless stones (Koolies, Dedeco Inc., USA) and inspected for any deformities. Discs were oxidized and labeled and divided into 4 groups according to number firing cycles. (Fig.3 A&B) (Table1)

TABLE (1) Sample grouping.

Group	No. Firing Cycles	No. Of samples
A	firing cycle 1	15
B	firing cycles 2	15
C	firing cycles 3	15
D	firing cycles 4	15
Total		60

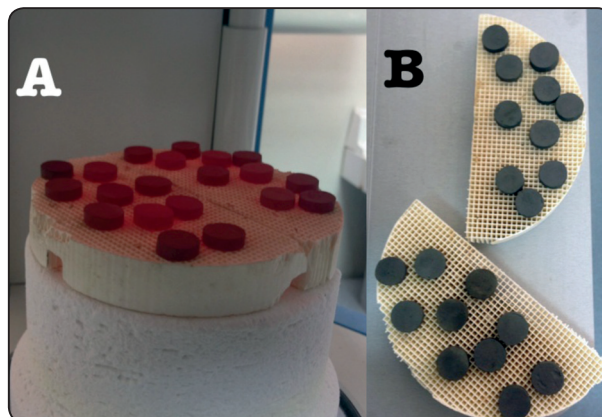


Fig. (3) A: metal discs during oxidation. B: metal discs ready for veneering.

Veneering procedure

The metal discs were veneered using the necessary amount of feldspathic ceramic (Duceram Kiss, DeguDent, Rodenbacher Chaussee 4, Wolfgang, Germany). The ceramic slurry was applied all at once onto the metal core using a slightly oversized silicon matrix. Excess moisture was removed using absorbent paper to compact the ceramic powder. Samples were placed in the furnace (ProFire2 compact, DeguDent, Wolfgang, Germany) and fired according to manufacturer's directions. (Fig.4 A&B) Specimens were divided into 4 groups ($n = 15$) according to number of firing cycles. All the specimens were thermocycled for 300 cycles with the sequence of 20 sec at 5°C and 20 sec at 55°C and 10 sec transport, then collected, labeled and stored in distilled water for 48 hours before testing. (Fig.5)

Shear bond strength test

A circular interface shear test was designed to evaluate the bond strength. All samples were individually mounted on a computer-controlled materials testing machine (Model LRX-plus; Lloyd Instruments Ltd., Fareham, UK) with a load-cell of 5 kN and data were recorded using computer software (Nexygen-MT; Lloyd Instruments). Samples were secured in a specially prepared metal mold to

the lower fixed compartment of testing machine by tightening screws. Shearing test was done by compressive load applied using a mono-bevelled chisel shaped metallic rod attached to the upper movable compartment of testing machine traveling at cross-head speed of 0.5 mm/min. The load required for debonding was recorded in Newton. (Fig. 6)

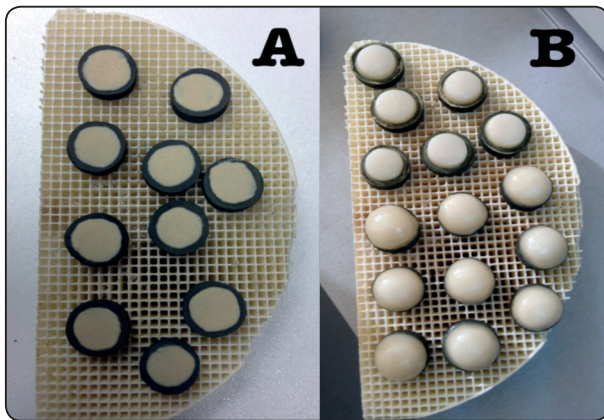


Fig. (4) A: Metal after placement of opaque layer. B: Top: Discs undergoing 2nd cycle. Bottom: Discs undergoing 1st cycle.



Fig. (5) Finished sample before testing.

Shear bond strength calculation

The load at failure was divided by bonding area to express the bond strength in MPa: ($\tau = P / \pi r^2$) where; τ = shear bond strength (MPa, P = load at failure (N) $\pi = 3.14$ and r = radius of veneer disc (mm)

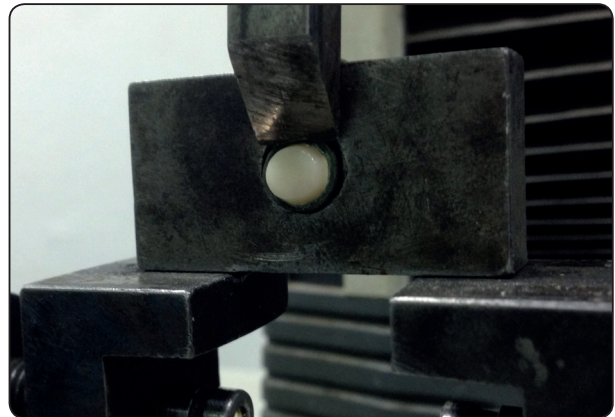


Fig. (6) Shear bond strength testing.

Failure mode scale

Fractured specimens (Fig.7) were ultrasonically cleaned, carefully checked under digital microscope (Dino-Lite, 241 Taiwan). All failures were classified into three modes:

1. Cohesive in porcelain veneer: Only the remnants of porcelain veneer were seen in the fractured surface.
2. Adhesive: No remnants of porcelain veneer on metal core.
3. Mixed: Both adhesive and cohesive failures were detected in the fractured surface.



Fig. (7) Fractured sample.

Statistical analysis

To determine the effects of firing cycles on shear bond strength of specimens, one-way ANOVA was used ($p < 0.05$). SPSS 16.0 v3.0 (SPSS, Inc., Chicago, IL, USA) was used.

RESULTS

The mean and standard deviation values between groups, are summarized in Table 2. The highest mean value was observed in group A (21.62 MPa) and the lowest mean value was observed for group B (19.29 MPa). Statistical analysis revealed no significant difference between groups ($P = 0.644$). Statistical analysis among groups showed no significant differences as well. (Table 3)

Regarding mode of failure; 100% of the samples showed mixed failure mode.

TABLE (2) The mean and standard deviation values between groups

	Mean	Standard Deviation
Group A	21.62	3.05
Group B	19.29	3.01
Group C	20.72	3.61
Group D	20.00	1.61

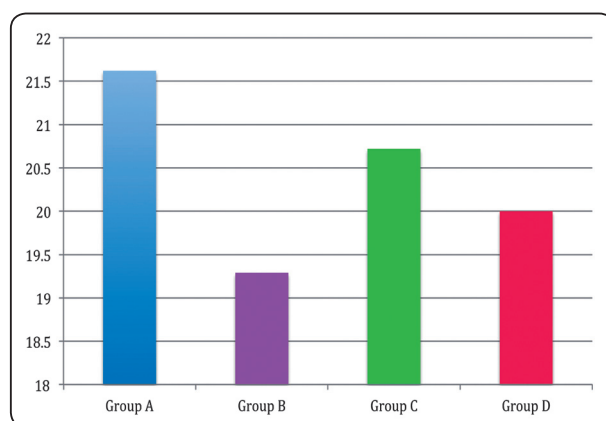


CHART (1) Mean values among groups

TABLE (3) P value among groups

	Group A	Group B	Group C	Group D
Group A		0.258	0.696	0.373
Group B	0.258		0.536	0.683
Group C	0.696	0.536		0.726
Group D	0.373	0.683	0.726	

DISCUSSION

The MCR is a combination of both ceramic and metal materials, combines the esthetic of porcelain and the strength and precise fit of the metal. ⁽²⁹⁾ So, How these two dissimilar materials bond together to function as a useful composite in dentistry? According to Wagner, there are three main factors that determine the success of the ceramic-metal bond: residual stresses, interfacial chemistry, and interfacial morphology. ⁽³⁰⁾ These three factors are inter-dependent and are difficult to evaluate individually. ⁽³¹⁻³⁵⁾

Every material has a coefficient of thermal expansion. The coefficient of thermal expansion (CTE) is defined as the fractional increase in length per unit rise in temperature. It is generally considered the alloy should have a higher CTE than the ceramic (termed positive coefficient mismatch) to produce axial compressive stress in the porcelain after cooling to room temperature. Since dental ceramics are much stronger under compression than tension, this residual compressive stress can effectively increase the bond strength. ⁽³⁶⁻³⁷⁾

This thermal compatibility of the metal-ceramic pair could play a significant role in bond strength because it constitutes the main physical requirement to avoid stress at the interface. ⁽³⁸⁻⁴¹⁾ The CTEs of the metal and ceramics must be compatible in order to avoid stress. ^(38,39,42-44) The recommended mean difference between alloy and ceramics CTEs (from room temperature to 600°C) is from 0.5 to 1.0 $10^{-6} \text{ }^{\circ}\text{C}^{-1}$. ^(44,45)

The success of a metal-ceramic restoration depends primarily on strong adhesion between the porcelain and alloy. Many methods have been proposed to quantify such adhesion, but none is completely exempt from errors, due to the complexity of the ceramic/metal bonding.⁽⁴⁶⁻⁴⁸⁾

Several authors in the literature suggested the use of shear bond strength test⁽⁴⁸⁻⁵⁵⁾, and considered it as one of the most reliable methods to evaluate the bond strength because it concentrates the applied tension on the interface between two materials.

Bonding between porcelain and metal is possible by means of three mechanisms: Van der Waals' forces, mechanical retentions and chemical bonding according.⁽⁵⁶⁾ Several studies demonstrated that preparation of the alloy surface resulted in an increase in bond strength between metal and porcelain surfaces. In this study mechanical retention it was used through sandblasting with Al_2O_3 (100 μ m) as a metal surface treatment.

Multiple firing procedures are essential to achieve better contour, color, and esthetics although there is no scientific data on the precise number of firing cycles to achieve a perfect ceramic restoration.⁽⁵⁷⁾ In the present study, there was no statistically significant difference between firing cycles for bond strength values. The result came in accordance with Stannard JG, et al, who observed no shear bond strength statistical difference after repeated firing.⁽⁵⁸⁾

Other studies^(48-50, 60) using the shear test with different methods and other types of alloys, reported results varying from 15 MPa to 60 MPa. The variation of the results in the studies is high, due mainly to the inexistence of a universal methodology for evaluation of bond strength of the porcelain fused to metal substrate.

As a relief, literature have described that shear bond strength mean greater than 10MPa indicate clinically satisfactory results.^(48, 60) The results of this study ranged from 19.3-21.6 MPa; within the safety borders.

Clinically, "ideal" metal-ceramic failure would be cohesive in nature (within porcelain). That is, the bond between metal and porcelain should be greater than the cohesive strength of the porcelain. Results of this study showed 100% mixed failure mode presenting unfavorable failure mode. As this failure mode clinically needs opaque composite and may be difficult to be optimally repair.

The hypothesis of this research was not fulfilled as firing cycles did not affect metal-ceramic bond strength. Further researches are needed to determine the bond strength using more ceramic-metal combinations and firing cycles. Regarding failure mode; all samples had mixed (cohesive adhesive) failure.

CONCLUSIONS

Within the limitation of the study, it could be concluded that; repeated firing cycles up to four cycles had no significant effect on shear bond strength of porcelain fused to metal.

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REFERENCES

1. Tan K, Pjetursson BE, Lang NP, Chan ES. A systemic review of the survival and complication rates of fixed partial dentures (FPDs) after an observation period of at least 5 years. *Clin Oral Implants Res* 2004;15:654-66.
2. Walton TR. A 10-year longitudinal study of fixed prosthodontics: clinical characteristics and outcome of single-unit metal-ceramic crowns. *Int J Prosthodont* 1999;12:519-26.
3. Spear FM. The metal-free practice: myth? Reality? Desirable goal? *J Esthet Restor Dent* 2001;13:59-67.
4. Heffernan MJ, Aquilino SA, Diaz-Arnold AM, Haselton DR, Stanford CM, Vargas MA. Relative translucency of six all ceramic systems. Part 1: core materials. *J Prosthet Dent* 2002;88:4-9.

5. Reitemeier B, Hänsel K, Kastner C, Walter MH. Metal–ceramic failure in noble metal crowns: 7-year results of a prospective clinical trial in private practices. *Int J Prosthodont* 2006;19:397–9.
6. Pjetursson BE, Sailer I, Zwahlen M, Hämmerle CH. A systematic review of the survival and complication rates of all ceramic and metal–ceramic reconstructions after an observation period of at least 3 years. Part I: single crowns. *Clin Oral Implants Res* 2007;18(Suppl. 3):73–85.
7. Sailer I, Pjetursson BE, Zwahlen M, Hämmerle CH. A systematic review of the survival and complication rates of all ceramic and metal–ceramic reconstructions after an observation period of at least 3 years. Part II: fixed dental prostheses. *Clin Oral Implants Res* 2007;18 (Suppl. 3):86–96.
8. Wettstein F, Sailer I, Roos M, Hämmerle CH. Clinical study of the internal gaps of zirconia and metal frameworks for fixed partial dentures. *Eur J Oral Sci* 2008;116:272–9.
9. Kelly JR. Clinically relevant approach to failure testing of all-ceramic restorations. *J Prosthet Dent* 1999; 81:652–661.
10. Pjetursson BE, Sailer I, Zwahlen M, Hämmerle CH. A systematic review of the survival and complication rates of all-ceramic and metal–ceramic reconstructions after an observation period of at least 3 years. Part I: Single crowns. *Clin Oral Implants Res* 2007;18(suppl 3):73–85.
11. Johanson M, Mosharraf S, Karlsson S, Carlsson GE. A dental laboratory study of the dimensions of metal frameworks for fixed partial dentures. *Eur J Prosthodont Restor Dent*. 2000;8(2):75–8.
12. Olsson KG, Furst B, Andersson B, Carlsson GE. A long-term retrospective and clinical follow-up study of In-Ceram Alumina FPDs. *Int J Prosthodont*. 2003;16(2):150–6.
13. Sorensen JA, Kang SK, Torres TJ, Knode H. In-Ceram fixed partial dentures: three-year clinical trial results. *J Calif Dent Assoc*. 1998;26(3):207–14.
14. Karlsson S. A clinical evaluation of fixed bridges, 10 years following insertion. *J Oral Rehabil*. 1986;13(5):423–32.
15. Palmqvist S, Swartz B. Artificial crowns and fixed partial dentures 18 to 23 years after placement. *Int J Prosthodont*. 1993;6(3):279–85.
16. Goodacre JC, Bernal G, Rungcharassaeng K, Kan JYK. Clinical complications in fixed prosthodontics. *J Prosthet Dent*. 2003;90(2):31–41.
17. Bradt RC, Evans AG, Hasselman DPH, Lange FF. Fracture mechanics of ceramics: microstructure, methods, design, and fatigue. Plenum Press; 1986.
18. Sundh A, Molin M, Sjorgen G. Fracture resistance of yttrium oxide partially-stabilized zirconia all-ceramic bridges after veneering and mechanical fatigue testing. *Dent Mat*. 2005;21:476–82.
19. Suresh S. Fatigue crack growth in brittle solids. In: Suresh S, editors. *Fatigue of materials*, 2nd ed. Cambridge University Press; 1998.
20. Tsuji K, Iwase K, Ando K. An investigation into the location of crack initiation sites in alumina, polycarbonate and mild steel. *Fatigue Fract Engng Mater Struct* 1999; 22:509–17.
21. Randow K, Glantz PO, Zoger B. Technical failures and some related clinical complications in extensive fixed prosthodontics. An epidemiological study of long-term clinical quality. *Acta Odontol Scand*. 1986;44:241–55.
22. Strub JR, Stiffler S, Schärer P. Causes of failure following oral rehabilitation: biological versus technical factors. *Quintessence Int*. 1988;19(3):215–22.
23. Kelly JR, Tesk JA, Sorensen JA. Failure of all-ceramic fixed partial dentures in vitro and in vivo: analysis and modeling. *J Dent Res*. 1995;74(6):1253–8.
24. Lüthy H, Filser F, Loeffel O, Schumacher M, Gauckler LJ, Hammerle CH. Strength and reliability of four-unit all-ceramic posterior bridges. *Dent Mat*. 2005;21(10):930–7.
25. Anusavice KJ. *Phillips's science of dental materials*. 11th Ed. Philadelphia:W.B. Saunders; 2003, p621–54.
26. Ozcan M, Niedermeier W. Clinical study on the reasons and location of the failures of metal–ceramic restorations and survival of repairs. *Int J Prosthodont* 2002; 15:299–302.
27. Craig RG, Powers JM. *Restorative dental materials* 11th ed. Mosby; 2002.
28. ISO 9693 Metal–ceramic bond characterization (Schwickerath crack initiation test) Geneva, Switzerland: International Organization for Standardization; 1999.
29. Fairhurst CW, Anusavice KJ, Hashinger DT, Ringle RD, Twigg SW. Thermal expansion of dental alloys and porcelain. *J Biomed Mater Res* 1980;14: 435–446.
30. Wagner WC, Asgar K, Bigelow WC, Flinn RA. Effect of interfacial variables on metalporcelain bonding. *J Biomed Mater Res*. 1993;27:531–7.
31. Shell JS, Nielsen JP. Study of the bond between gold alloys and porcelain. *J Dent Res* 1962;41:1424–143.

32. Murakami I, Schulman A. Aspects of metal-ceramic bonding. *Dent Clin North Am*, 1987;31 :333-46.
33. Knap F, Ryge, G. Study of bond strength of dental porcelain fused to metal. *J Dent Res* 1966;45:1047-51.
34. Anusavice KJ, Ringle RD, Fairhurst CW. Bonding mechanism evidence in a ceramic-non precious alloy system. *J Biomed Mater Res* 1977; 11: 701-709.
35. Szantho von Radnoth M, Lautenschlager EP. Metal surface changes during porcelain firing. *J Dent Res* 1969; 48: 321-4 .
36. Lund PS, Goodkind RJ, Swanson S. Residual stress in several ceramometal systems. *J Prosthet Dent* 1989;62: 278-83.
37. Coffey JP, Anusavice KJ, Dehoff PH, Lee RB, Hojjatie B. Influence of contraction mismatch and cooling rate on flexural failure of PFM systems. *J Dent Res* 1988;67:61-5.
38. DeHoff PH, Anusavice KJ, Hojjatie B. Thermal incompatibility analysis of metal-ceramic systems based on flexural displacement data. *J Biomed Mater Res*. 1998; 41:614-23.
39. Fairhurst CW, Anusavice KJ, Hashinger DT, Ringle RD, Twigg SW. Thermal expansion of dental alloys and porcelains. *J Biomed Mat Res*. 1980;14:435-46.
40. Oilo G, Johansson B, Syverud M. Bond strength of porcelain to dental alloys - an evaluation of two test methods. *Scand J Dent Res*. 1981;89:289- 96.
41. Walton TR, O'Brien WJ. Thermal stress failure of porcelain bonded to a palladium-silver alloy. *J Dent Res*. 1985;64:476-80.
42. Anusavice KJ, DeHoff PH, Fairhurst CW. Comparative evaluation of ceramic-metal bond tests using finite element stress analysis. *J Dent Res*. 1980;59:608-13.
43. Anusavice KJ, Shen C, Hashinger D, Twigg SW. Interactive effect of stress and temperature on creep of PMF alloys. *J Dent Res*. 1985;64:1094-9.
44. Steiner PJ, Kelly JR, Giuseppetti AA. Compatibility of ceramic-ceramic systems for fixed prosthodontics. *Int J Prosthodont*. 1997;10:375- 80.
45. Anusavice KJ. Dental casting and soldering alloys. In: Phillips Science of Dental materials. 11th ed. Philadelphia: Saunders; 2003. p. 563-620.
46. Hegedus C, Daróczy L, Kökényesi V, Beke DL. Comparative microstructural study of the diffusion zone between Ni-Cr alloy and different dental ceramics. *J Dent Res* 2002; 81:334-7.
47. Chong MP, Beech DR. A simple shear test to evaluate the bond strength of ceramic fused to metal. *Aust Dent J* 1980; 25:357-61.
48. Hammad IA, Stein RS. A qualitative study for the bond and color of ceramometals – Part I. *J Prosthet Dent* 1990; 63:643-53.
49. Daftary F, Donovan T. Effect of four pretreatment techniques on porcelain-to-metal bond strength. *J Prosthet Dent* 1986; 56:535-9.
50. Malhotra ML, Maickel LB. Shear bond strength in porcelain- metal restorations. *J Prosthet Dent* 1980; 43:397-400.
51. O'Connor RP, Mackett JR, Myers ML, Parry EE. Castability opaque masking and porcelain bonding of 17 porcelain-fused- to-metal alloys. *J Prosthet Dent* 1996; 75:367-74.
52. Bondioli IR, Bottino MA. Evaluation of shear bond strength at the interface of two porcelains and pure titanium injected into the casting mold at three different temperatures. *J Prosthet Dent* 2004; 91:541-547.
53. Lubovich RP, Goodkind RJ. Bond strength studies of precious, semiprecious, and nonprecious ceramic-metal alloys with two porcelains. *J Prosthet Dent* 1977; 37:288-99.
54. Stannard JG, Marks L, Kanchanatawewat K. Effect of multiple firing on the bonding strength of selected matched porcelain-fused-to-metal combinations. *J Prosthet Dent* 1990; 63:627 – 9.
55. Kimura H, Horng CJ, Okazaki M, Takahashi J. Oxidation effects on porcelain-titanium interface reactions and bond strength. *Dent Mat* 1990; 9:91-9.
56. Anusavice KJ, Dehoff PH, Fairhurst CW. Comparative evaluation of ceramic-metal bond tests using finite element stress analysis. *J Dent Res* 1980; 59:608-13.
57. Mohammad M. Rayyan, Effect of Multiple Firing Cycles on the Shear Bond Strength and Failure Mode between Veneering Ceramic and Zirconia Cores. *Egyptian Dental Journal*, Vol. 60, 3325:3333, July 2014
58. Stannard JG, Marks L, Kanchanatawewat K. Effect of multiple firing on the bond strength of selected matched porcelain-fused-to-metal combinations. *J Prosthet Dent*. 1990 Jun;63(6):627-9.
59. Poliak-Guberina R, Catovic A, Jerolimov V, Franz M, Bergman V. The fatigue strength of the interface between Ag-Pd alloy and hydrothermal ceramic. *Dent Mat* 1999; 15:417-20.
60. Gale MS, Darvell BW. Thermal cycling procedures for laboratory testing of dental restorations. *J Dent* 1999; 27:89-99.