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RESEARCH ARTICLE

METAL CERAMIC BONDING AND TEST DESIGNS FOR IN VITRO METAL CERAMIC BOND EVALUATION

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ABSTRACT

All-ceramic anterior restorations can appear very natural. Unfortunately, the ceramics used in these restorations are brittle and subject to fracture from high tensile stresses. Fortunately the esthetic qualities of ceramic materials can be combined with the strength and toughness of metals to produce restorations that have both a natural tooth like appearance and very good mechanical properties. As a result they are more successful as posterior restorations than all-ceramic crowns. The cast metal coping provides a substrate on which a ceramic coating is fused. The ceramics used for these restorations are porcelains, hence the common name, porcelain-fused-to-metal restorations. Fractures of these Metal ceramic restorations happen at different levels, and the restorations themselves are subjected to various types of stresses. This article describes test designs which can evaluate the strength of the metal ceramic bond in a laboratory setup, mainly flexural and tensile tests, to enable us to evaluate the newer ceramics to be used in a clinical setup, with advantages and shortcomings of the same.

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INTRODUCTION

The success of metal ceramic crowns and fixed bridges depend upon the firmness of the bond between metal and ceramic. The accurate measurement of the bond strength at the ceramo–metallic junction presents formidable problems, since the complexity of the bonding probably defies the development of a single test experiment (McLean, 1980). One of the established bond-strength tests is the planar shear test. Other commonly used tests are the flexural tests. The flexural tests require layers of ceramic to be bonded to a strip or plate of metal. The coated metal plate is flexed in a controlled manner until the ceramic fractures off. In the 3-point flexure bend test, ceramic is fired to one side of a rectangular strip of metal. The metal-ceramic strip is supported by two knife edges, and the specimen is loaded in the center with the ceramic surface down until failure of the ceramic occurs. An adequate bond occurs when the fracture stress is > 25 MPa; however, with many metal-ceramic systems values of 40 to 60 MPa are common. In a variant of this test, opaque and body ceramics are applied and fired to a thickness of approximately 1 mm on a 20-mm x 5-mm x 0.5-mm alloy sheets. The specimen is then bent over a 1-cm-diameter rod (with the ceramic on the outside) and then straightened. The surface is viewed under low magnification and the percent of the surface with retained ceramic is reported. Tests based on tensile and torsional loading schemes have also been used.

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Requirements for a ceramic-metal system

1. High fusing temperature of the alloy. The fusing temperature must be substantially higher (>100° C) than the firing temperature of the ceramic and solders used to join segments of a bridge.
2. Low fusing temperature of the ceramic. The fusing temperature must be lower than ceramic used for all-ceramic restorations so no distortion of the coping takes place during fabrication.
3. The ceramic must wet the alloy readily when applied as slurry in order to prevent voids forming at the interface. In general, the contact angle should be 60 degrees or less.
4. A good bond between the ceramic and metal is essential and is achieved by the interactions of the ceramic with metal oxides on the surface of metal and by the roughness of the metal coping.

5. Compatible coefficients of thermal expansion of the ceramic and metal so the ceramic does not crack during fabrication. The system is designed so the value for the metal is slightly higher than for the ceramic, thus putting the ceramic in compression (where it is stronger) during cooling.
6. Adequate stiffness and strength of the alloy core. This requirement is especially important for fixed bridges and posterior crowns. High stiffness in the alloy reduces stresses in the ceramic by reducing deflection and strain. High strength is essential in the interproximal regions in fixed bridges.
7. High sag resistance is essential. The alloy copings are relatively thin; no distortion should occur during firing of the ceramic or the fit of the restoration will be compromised.
8. An accurate casting of the metal coping is required even with the higher fusing temperature of the alloy.
9. Adequate design of the restoration is critical. The preparation should provide for adequate thickness of alloy and also provide enough space for an adequate thickness of ceramic to yield an esthetic restoration. In some instances, a ceramic-metal restoration has an advantage over an all-ceramic restoration because less tooth structure needs to be removed to provide adequate bulk for the all-ceramic restoration. However, in cases of small, lower, anterior teeth, an all-ceramic restoration has an advantage with respect to esthetics, because with a ceramic-metal restoration it is difficult to remove enough tooth structure to provide space for the coping and the esthetic ceramic layer. The geometry of the shoulder should be flat with a rounded angle or a chamfer to allow enough bulk of ceramic and avoid fracture in this area. If full ceramic coverage is not used (e.g., a metal occlusal) the position of the ceramic-metal joint should be located as far as possible from areas of contact with opposing teeth.

Ceramic-metal bonding

The nature of this ceramo-metallic bond may be divided into the following components (McLean, 1980) :

Mechanical- surface tension provides intimate contact of porcelain with the micro surface irregularities of the metal. From both theoretical and practical standpoints, the roughness, and more generally the topography, of a ceramic-metal interface plays a large part in adhesion. The ceramic penetrating into a rough metal surface can mechanically interlock with the metal, like Velcro, improving adhesion. The increased area associated with a rougher interface also provides more room for chemical bonds to form. However, rough surfaces can reduce adhesion if the ceramic does not penetrate into the surface and voids are present at the interface; this may happen with improperly fired porcelain or metals that are poorly wetted by the porcelain. Sandblasting is often used to remove excess oxide and to roughen the surface of the metal coping to improve the bonding of the ceramic.

Chemical- bulk diffusion of base metal atoms produces an oxide film on the metal surface which forms a chemical bond with the porcelain (McLean, 1980). The bond strength between the ceramic and metal is perhaps the most important requirement and thus will be given special attention. In general, the bond is a result of chemisorption by diffusion between the surface oxides on the alloy and in the ceramic. These oxides are formed during wetting of the alloy by the ceramic and firing of the ceramic. The most common mechanical failure of these restorations is ceramic de-bonding from the metal. Many factors control metal-ceramic adhesion: the formation of strong chemical bonding, mechanical interlocking between the two materials, and residual stresses. In addition, the ceramic must wet and fuse to the surface to form a uniform interface with no voids. Base-metal alloys contain elements, such as nickel, chromium, and beryllium, which form oxides easily during degassing, and care must be taken to avoid too thick an oxide layer.

Compression- Sintering shrinkage and thermal contraction of the porcelain will be resisted by the metal and compressive stresses will be set up in the porcelain. The porcelain will be firmly bonded to the metal (McLean, 1980). High residual stresses between the metal and ceramic can lead to failure. If the metal and 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 ceramic on the restoration will crack or separate from the metal. Even if the stresses are less strong and do not cause immediate failure, they can still weaken the bond. To avoid these problems the ceramics and alloys are formulated to have closely matched thermal expansion coefficients. Most porcelain have coefficients of thermal expansion between 13.0 and 14.0 x 10^{-6}/° C, and metals between 13.5 and 14.5 x 10^{-6}/° C. The difference of 0.5 x 10^{-6}/° C in thermal expansion between the metal and ceramic causes the metal to contract slightly more than does the ceramic during cooling after firing. This condition puts the ceramic under slight residual compression, which makes it less sensitive to applied tensile forces.

Evaluation of ceramic-metal bonding

Several tests have been used to assess the strength of the ceramo-metallic bond in dental restorations. Shell and nelson devised a test in which a14 gauge wire (1.63mm diameter) was embedded in a block of porcelain to a depth of about 2.5mm and the stress to pull it out was measured (Shell and Neilsen, 1962). Another test devised by Lavine and Custer (1966) used a flat strip of metal with the porcelain baked onto the tensile face which was then tested for transverse test modulus of rupture) (Lavine and Custer, 1969). Knapp and Ryge used a different approach and strained a porcelain coated alloy rod and then measured the energy to initiate and propagate fracture (Knapp and Ryge, 1966). Sced and McLean designed a test piece (Fig. 1) based on a standard metallurgical tensile test piece, except for modification of the metal face which is made conical in order to place the bond in the direction of maximum shear stress (Sced *et al*., 1972). However, none of these test methods can be regarded as ideal and the problem of residual stresses interfering with the results must be taken into account. The selection of the best test piece is therefore a question of deciding which one produces the least amount of residual stress at the bond.

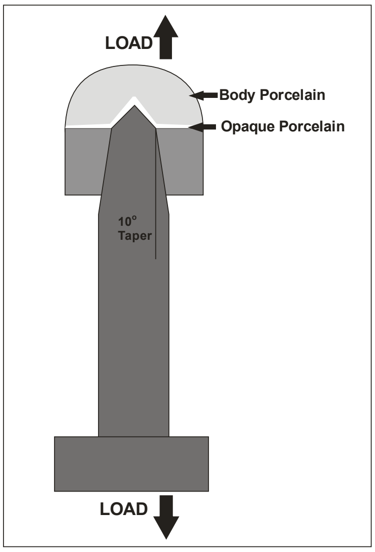

Fig. 1. Conical interface test design (Seed and McLean, 1972)

In the clinical setup the when a bridge is involved the maximum stress are of tensile or flexural type in this article the various test specimens considering the above mentioned stresses will be discussed and evaluated, considering the clinical importance of these test specimens.

Tensile Stress

Tensile tests have been mainly used for measurement of oxide adherence to ceramic alloys (Hammad *et al*., 1996; Mackert *et al*., 1984; Peregrina *et al*., 1992). The test samples consisted of oxidized alloy plates luted between two metal rods with a high-strength luting agent. Samples were loaded in tension until separation, and post-tested samples were then examined to evaluate oxide adherence. Metal-ceramic tensile tests consisted of porcelain fired on one end of a metal rod or between ends of two metal rods (Fig. 2, 3).

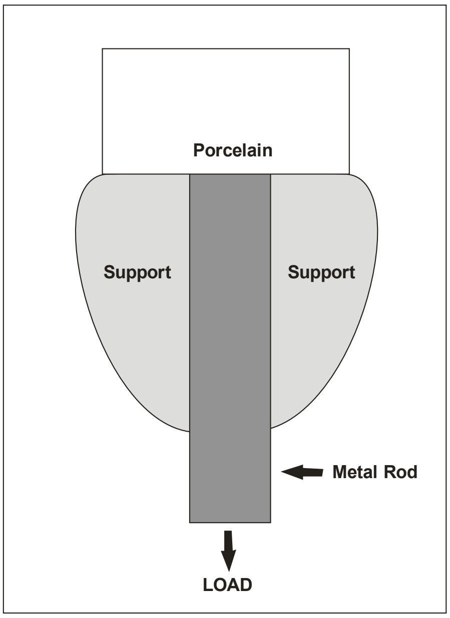

Fig. 2. Ceramo-metal tensile test design. Porcelain fired on one end of metal (Kelly *et al.,* 1969)

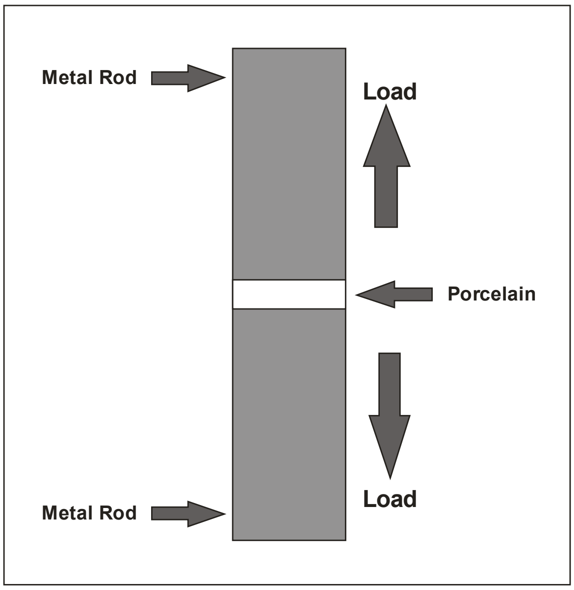

Fig. 3. Ceramo-metal tensile test design. Porcelain fired between two metal rods

Longitudinal tensile force was then applied to separate porcelain from the metal. Kelly *et al*. (1969), developed a tensile test so that porcelain was fired on the end but not the shank of a cylindrical rod casting. This preparation of the specimen was accomplished with a platinum matrix and minimal shearing stresses, Tensile tests have been criticized because of alignment difficulties and a possibly of notching on the external surface of porcelain. Consequently, this allowed irregular stress distribution with cohesive failures within porcelain. This indicated that the strength of an interfacial bond was greater than strength of a porcelain cross section. Cohesive failure of porcelain, not interfacial bond strength, was actually evaluated (McLean and Seed, 1973; McLean and Seed, 1973; Nally, 1968).

Combination shear-tension tests

A shear-tension test adapted from the American Society for Testing Materials (ASTM) test version D-2295-72 was developed by Wight *et al*. (1977) (Fig. 4).

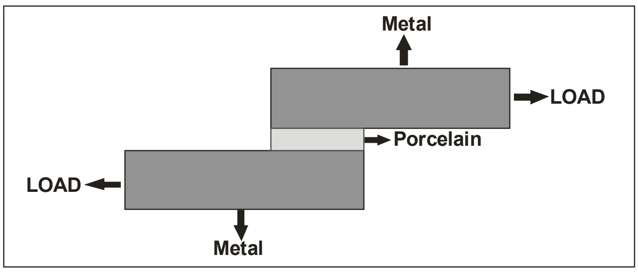

Fig. 4. Combination shear-tension test (Wight *et al.,* 1977)

Because of two bonding interfaces that were not aligned at the middle of the thickness of each specimen, forces were not primarily directed at metal-ceramic interfaces. Instead, test loading was directed diagonally for development of a combination of shear and tensile stresses to simulate complex, clinical stress situations. Consequently, cohesive porcelain failures were reported (Hammad and Yousef F. Talic, 1996; Wight *et al*., 1977) but porcelain thicknesses were not accurately controlled.

Bend tests (flexure)

The bend test with three- or four- point loading was selected by Lavine and Custer (1966) (Fig. 5) Caputo (Caputo *et al*., 1976; Caputo *et al*., 1977) (Fig. 6) and O'Brien and Craig (1977) (Fig. 7). A flat strip of metal was used with porcelain fired on the tensile face, which was then tested for transverse strength (modulus of rupture). Transverse strength is breaking strength in a non ductile solid, such as porcelain, measured by bending (Van Vlack, 1964). This is usually identified as bend strength on flexural strength (Dowling, 1993).

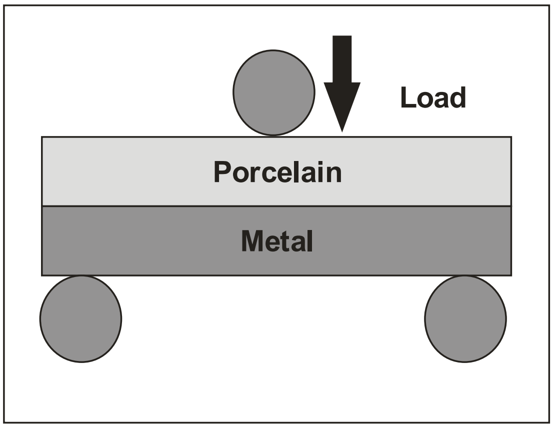

Fig. 5. Bend test designs. Three-point loading (Lavine and Custer 1966)

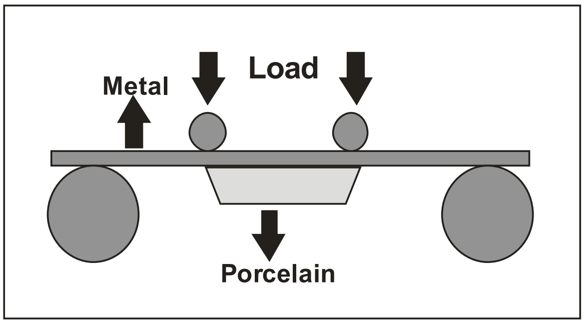

Fig. 6. Bend test designs. Four-point loading (Caputo *et al*. 1976, 1977)

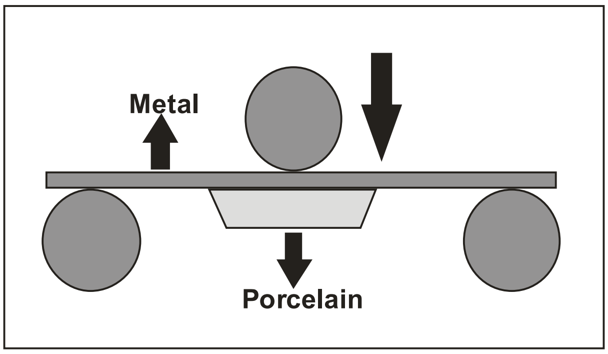

Fig. 7. Bend test designs. (O'Brien and Craig, 1992)

Finite element stress analysis demonstrated higher tensile stresses compared with shear stresses, creating a greater probability of tensile failures (Anusavice *et al*., 1980). Tensile stresses could be either perpendicular or parallel to a metal-ceramic interface. The relative importance of each tensile stress directional component remains un- known (Anusavice, 1983). Caputo *et al*. (1976) reported that a four-point loading test reduced the possibility of the tensile failures occurring in three-point loading tests and relatively greater interfacial shear stresses were developed. Four-point loading tests were successfully used to separate porcelain from metal when interfacial failures consistently developed at load points with microscopically clean separation between porcelain and metal (Caputo et al., 1976). Four point loadings were also easy to fabricate, required no special equipment for testing, and thicknesses of porcelain and metal simulated clinical conditions (Caputo *et al*., 1976). Another bend test that used a semicircular arch was used by Mackert *et al*. (1976) and Anusavice *et al*. (1979) (Fig. 8). This test demonstrated lower stress concentrations and greater probability of tensile failures compared with three point or four-point loading flexure tests (Anusavice *et al*., 1980). Bend tests were subject to criticism because maximal tensile stresses were created at the surface of porcelain and resulted in predictable tensile failures (Anusavice *et al*., 1980; McLean, 1980). The major difficulty with bend tests was related to analysis of stress states that were present. The validity of these tests to evaluate different alloys has been questioned because ceramic breakage depended on the modulus of elasticity of the metal tested. An alloy with an elevated modulus of elasticity would resist bending to a higher bond (Hammad *et al*., 1987). Therefore it becomes suspect as to whether the bond or the modulus of elasticity of the metal is the characteristic actually tested.

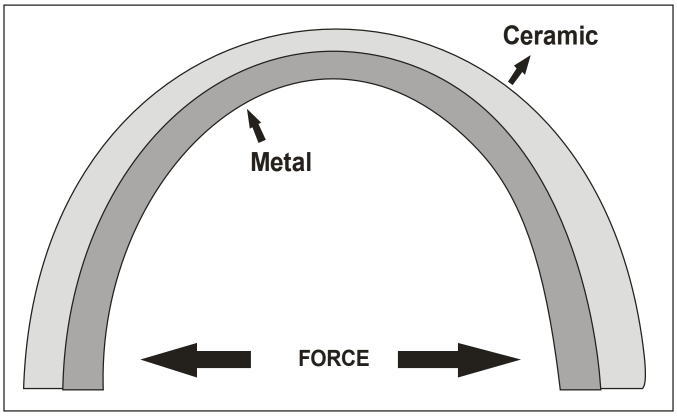

Fig. 8. Semicircular bend test design (Mackert *et al*., 1976)

Torsion test

Carter *et al*. (1996, 1979) evaluated metal-ceramic bond strengths by use of a torsion test. Test samples consisted of metal plates with porcelain applied on both sides (Fig. 9). This difficult task was achieved with a special jig. After porcelain firing, the samples were mounted to a torsional device attached to an Instron testing machine. Two-dimensional finite element stress analysis and calculation of stress distribution were extremely difficult because of the complexity of this test design (Anusavice, 1983).

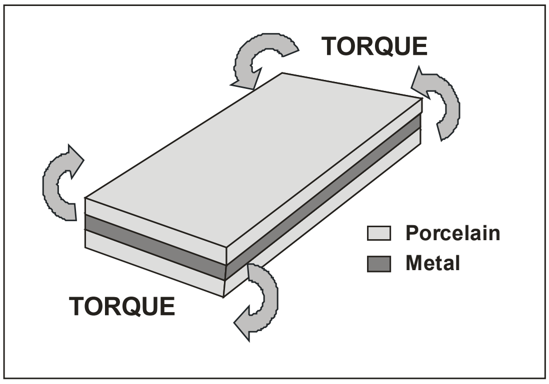

Fig. 9. Torsion test design (Carter *et al*., 1979)

Summary

Many tests have been used to determine the bond strength between ceramics and metals; however, the ideal test currently does not exist. In addition, data obtained from different tests are often not comparable. All the present tests can only give a measure of the strength of a metal-ceramic system under a defined state of loading. It is unlikely that any test can be devised which will give an absolute measure of the adhesion of porcelain to metal except in case where the adhesion strength is lower than the tensile strength of the porcelain and the metal-porcelain couple is so exactly matched as to be stress free (Hammad *et al*., 1996). The most reliable evaluation of metal-ceramic bond strengths should be based on minimal experimental variables and least residual stresses at metal-ceramic interfaces. Evaluation for types of metal-ceramic failures is critical even though cohesive failures within porcelain have been an indication of clinically acceptable metal-ceramic bonds (Hammad *et al*., 1996). Although laboratory studies offer predictable guidance to comprehensive selection of materials, clinical longitudinal studies should also be encouraged to complement laboratory results and enhance clinical standards. Furthermore, any clinical precaution that contributes to an improved bond between porcelain and metal would ensure the longevity of metal-ceramic restorations (Hammad *et al*., 1996).

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