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Dental Ceramics

Conference on Recent Developments in Dental Ceramics

**Proceedings of Conference on
Recent Developments in Dental Ceramics**

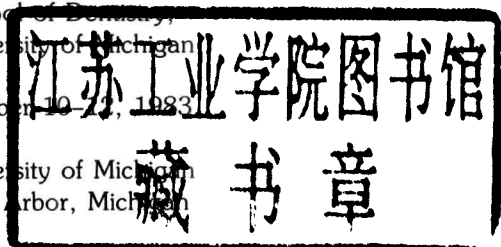
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Robert G. Craig
Editors**

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Preface

The proceedings of this Conference present information on new materials and processes being used in the fabrication of dental crown and bridges. The use of porcelain as denture teeth goes back to the 18th Century. Over the past 25 yr dental ceramics have become the main materials for the construction of dental crowns. These applications include all ceramic crowns and porcelain fused to metal crown and bridgework. The cost of fabrication for these applications has been estimated to be in the area of one billion dollars annually in the United States. Also included in the proceedings are the transcripts of the recorded questions and answers after each presentation. Unfortunately, most of the people asking questions did not give their names. Therefore, no names were used. We wish to thank Mrs. Cara Voss for typing the transcripts from the original recordings. However, many of the manuscripts were rewritten by the authors in a more suitable style for publication. We wish to thank the authors for their cooperation in producing the manuscripts and to Dr. Arthur L. Friedberg for agreeing to publish the proceedings.

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Current Status and Future of Ceramics in Dentistry

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The strengths and appearance properties of aluminous porcelain are compared with the new injection-molded and cast ceramics for use in dental crown and bridgework. Clinical failure rate data with platinum-bonded aluminous porcelain indicates acceptable strength for anterior, but not for posterior crowns. Since injection-molded spinel ceramics are no stronger, their application is also limited. Although the glass-ceramics have a greater potential for higher strength, they require surface staining which reduces their esthetic possibilities.

Development of ceramics in dentistry has progressed from glass-ceramics to high-alumina ceramics to aluminous porcelain. The flexural strengths of hot-pressed materials like silicon nitride and silicon carbide are enormous but from the point of view of dentistry not very suitable because they are black and most people do not like black crowns! The flexural strength of dental porcelain of about 61–80 MPa is rather low. If one considers metals, for example an average gold alloy, the yield strengths of these alloys are roughly equivalent to the flexural strengths of high alumina (500 MPa). It is quite certain, and evidence will be presented, that if ceramics are to be used in fixed bridges, strengths of the order of those of high alumina are needed, otherwise on a long-term basis, catastrophic failure will occur. Even if glass ceramics are considered, where present information indicates values as high as 300 MPa, these strengths probably are insufficient. Individual crowns can be made but bridgework is a more difficult problem, particularly where connectors have cross-sectional areas of less than 2.5 mm.

If methods of strengthening ceramics are examined, at the top of the list is the enameling of metals. Following enameled metals is dispersion strengthening which includes the aluminous porcelains and the special ceramic,* since it is also a dispersion-strengthened material. The enameling of crystalline ceramics follows where aluminous porcelain bridges are connected with high-alumina rods and a veneer porcelain is baked onto it in a way similar to the enameling of metals.

The crystallization of glass is well known today, and this approach has been tried in dentistry. McCullough¹ of Great Britain published work with Pilkingtons on glass-ceramics. It is referenced in my book.² He used lithia-zinc oxide-silica glass as the starting base and made teeth "in which bars of the vitreous glass were made photosensitive by using silver as a nucleating agent." The interesting thing about McCullough's work was that he differentiatingly radiated the surface of the glass and, upon heating to the ceraming temperature, crystallization occurred at different rates in various portions of the tooth, thus creating a polychromatic effect. It was shown that further characterization might be accomplished by applying printed transfers con-

taining tooth pigments to the surface. The problems with glass-ceramics will be discussed later, particularly in relation to McCullough's original work.

The platinum-bonded alumina crown was developed recently by me. I have conducted a seven-year clinical evaluation involving a large number of restorations. The original concept was to use a high-strength aluminous porcelain core as the reinforcing agent and veneer porcelains would be built up by hand to produce individual layering and characterization effects that are seen in human enamel. The original alumina porcelains we developed³ were made with a 400-mesh fused alumina because it would provide increased translucency. As the particle size decreases to 5 μm or less, increased opacity results. One of the problems with using any of these aluminas was that the raw material supply was difficult and the crystals were very jagged. Ideally, a much smoother crystal interface is desired for bonding to the glass phase. It was found that at increased loadings, increased interference between the edges of the crystal in the glass phase occurred, and this increased the risk of porosity. Improvements in crystal shape, ratio, and size have taken place as well as improvements in presintering. If finer crystals are used and you presinter at higher temperatures, up to 1400°C, a glass melt of crystal can form and the glass can then be reground. This change will give the dentist or technician a much better opportunity to produce a porous-free ceramic. I predict that for aluminous porcelains much higher sintering temperatures will be used, the crystals will be more finely graded, and higher loading will be added. This is one possible direction to go because a useful material will be produced that can be sintered to full density.

The mechanism of strengthening is well known. If one examines crack propagation in ceramics, it is generally agreed that two strengthening mechanisms exist. The one proposed by Hasselman and Fulrath⁴ results from the close packing of the crystals which reduces the surface flaw area of the glass, therefore fewer microcracks will propagate. Secondly as Binns⁵ has shown, the crystals and the glass act as a constant strain system, and fracture has an equal chance of passing through either phase because the higher modulus of the crystals results in it bearing a greater proportion of the load. For ceramic bridges to survive they must be fabricated from alumina products with about 75% alumina in the body. We have made some experimental bridgeworks with 75 to 98% alumina and they stood up fairly well, because they have virtually the strength of metals. The main problem was commercializing them, because the shrinkage factor with high alumina is tremendous. Recrystallization takes place by a shift of grain boundaries, and generally the bigger crystals grow at the expense of the smaller ones. A close interlocking crystalline mass forms with atomic exchange going on at the boundaries and a shift of crystal boundaries until a really dense-packed crystalline material results which imparts the strength to high alumina. This strength cannot be reached without exposure to fairly high temperatures, which is not a serious problem. The major concern is that there is no pyroplastic flow. Thus, there is no means of the material slumping and fitting either onto platinum, refractory dies, or whatever you care to use. If high strength is desired recrystallization is required, and insufficient glass phase exists to enable the restoration to fit.

When this problem was appreciated aluminas were debased to the point where sufficient pyroplastic flow occurred to make it clinically viable. Pyroplastic flow is required unless a nonshrinking material such as the special ceramic* is used. The strength of the aluminous ceramic ended up at about

170–210 MPa (25–30 000 psi). These values were the optimum since a glass phase was necessary to make it clinically viable. That is the current status except there is the possibility of presintering and making actual molten glass mixes with alumina. It is doubtful that strengths above 210 MPa (30 000 psi) are feasible. High alumina is so strong because the grain boundaries shift and porosity tends to get swept out at these boundaries. This is precisely why this material[†] is translucent. Magnesium oxide is added to form a spinel at the grain boundaries, slow down grain growth, and get rid of porosity.

If the early bridges are examined for esthetics, it is apparent that the pure alumina bridge was a beautiful restoration, and a good fit could be obtained. The high-alumina reinforcing rods across the pontic area were quite easily inserted, with the result that a delightful interproximal glaze could be produced, particularly in the embrasure spaces so that everything was very clean. At that time the alumina bridge looked very promising, but events showed that fracture was too high.

A German company actually made high alumina backings that were veneered in the front with aluminous porcelain to create production teeth. The idea was to eliminate pins. With the dovetail backing it could be used either on a bridge or on a denture with a slenderline tooth. The principal problem in the factory was controlling the firing shrinkage of the veneer porcelains. This problem was never really conquered to the degree that they could be produced commercially, but a lot of teeth were made. At this stage it appeared that metal was hard to beat. The great advantage of metal is that if you get a crack, slip and dislocations tend to heal it a little and rapid crack propagation through fairly ductile metals does not usually occur. If the mechanism of breakage of the average ceramic bonded to metal is examined it can only occur in the metal or ceramic. Usually fracture results from an internal pore under stress from which cracks propagate. As a clinical system it has been well established as a major clinical success.

Based on this idea we found that by bonding porcelains, even to thin foil, marked strength increases were observed. This was the start of the platinum-bonding studies where aluminous porcelain was bonded to platinum via tin oxide coatings. The strength of the alumina core was utilized, and the foil reduced "static fatigue" failure which is believed to be a major cause of breakage of crowns over long periods (Fig. 1). Crack propagation is often initiated through static fatigue by moisture contamination.

Many people, particularly in the United States, found they could not make the platinum-bonded crowns fit. This was not found to be true in Europe because the Health Service in Britain last year turned out about 16 000 platinum-bonded crowns. This year, the figure has increased to over 30 000. These restorations are being turned out by dental laboratories for prices as low as 10 pounds (14 dollars) a crown, including the cost of the platinum. From a functional point of view, it has been found that bonding to platinum foil is reducing the long-term effects of static fatigue.

We have tried to simplify the system by using a single-foil technique. What is done is to prepare the die using a die spacer of five coats to create room for the cement. A single foil is laid down over the die spacer, and on the actual shoulder area wax is melted on to protect the platinum against the tin plate. The foil is lightly sandblasted and tin plated, which takes about three min. After tin plating and oxidizing, if you burn off the wax, or boil it off, an oxidizable surface will remain on *the axial walls* with the shoulder free of any

tin plating. A double-bake system is used even though it is more time consuming. The following procedure may be tried. A thin slurry of alumina porcelain is painted over the tin oxide and it is fired for a minimum of 10 min at 1150°C to result in total wetting of the tin oxide-coated axial foil. The bulk build-up can then be done. This procedure reduces the problem of shrinkage and problems at the margin. When total wetting of the surface occurs, if the platinum is peeled off, a cohesive break in the porcelain occurs. By contrast, when unplated platinum is used, pore strata occurs from which cracks can propagate. This is why I think the platinum-bonded ceramic works. Apprentice technicians are producing fits with these restorations, showing less than 20 μm marginal opening, without any great difficulty. The technique may be learned within a week.

With the double-bake system, and using sintered diamond stones to very finely trim the margin, a high-strength core material bonded to the platinum foil is obtained. When the outer edge of platinum has been removed and the crown is seated, fits in the region of 5–10 μm are obtained by skilled technicians without a great deal of difficulty. Even with patients who have suffered loss of gingival height due to periodontal disease, supragingival restorations can be treated successfully.

It is considerably more difficult to fire porcelain to a knife edge of metal than it is to a butt joint of platinum foil. In the former, one obtains a roll of porcelain away from the free edge of metal because of surface tension effects. In order to get a good fit, the technician would have to go back about five times and rebake little pieces all the way around. Therefore fused porcelain to metal crowns with a knife edge never truly fit. A gold collar with or without a bevel is preferred, but cannot always be used for aesthetic reasons.

Using the Timoshenko disc breaking-stress test at the National Physical Laboratory London, Dr. Sced and I found that discs with no tin coating broke at about 90 MPa, and with a tin coating at about 140 MPa using a German aluminous-core porcelain.[‡] With the current material,[§] in which the glass phase has been increased to get better wetting, the tin coating system gave strengths of about 155 MPa that compares to 60 MPa with regular dental porcelain. Thus the strengths can be increased markedly by bonding the ceramic to thin metal coatings. It might be possible to increase the strength of bridgework by firing nonshrinking ceramics onto thin foil. In any event, the metal coating system is a good way of reducing some of the static fatigue problems. Minassian⁸ performed tests on porcelain jacket crowns in which he cemented them to dies, and loaded them in a manner similar to the method used by Munos.⁹ Minassian obtained increased strengths with the bonded platinum crown, whereas Munos of Indiana did not. We do not agree with the latter result because the overwhelming opinion of testing around the world shows quite conclusively that bonding to metal foils, whether it is platinum or gold, effectively strengthens porcelain.

A complete series of these crowns from 1974 to 1980 have been followed. I have not been able to examine every single one, nevertheless a large percentage have been observed. The percentage failure rate with bonded alumina crowns is shown in Table I. The failure rate for molars in my opinion is too high and totally unacceptable clinically. Failure rates decrease from the premolars to canines to incisors. These data are an indication of the stresses involved because it is quite clear that when you consider incisal guidance in relation to canine protection, the front teeth are placed under less stress. What

concerns me about glass-ceramics or even the special ceramic,* is that, unless there is a great deal of material occlusally on molars, serious trouble can result. If the central fossa area decreases to a 1/2 mm coping thickness, over a long period of testing a fracture will occur sooner or later. Clinical testing should extend over a minimum period of five yr if reasonable observations on the success of high strength ceramic are to be obtained. As a result of my own testing, I am convinced that unless you can obtain at least 400 MPa flexural strength, there is an insufficient safety factor in the average practitioner's hands. He is not going to reduce the occlusal surface to the degree that is desired, in fact, he may not be able to do so. If the material demands 1.5 mm occlusal clearance, biologically speaking, you are severely reducing tooth structure. This is another reason why metal is very difficult to beat and fused porcelain-to-metal is a remarkable system. On the other hand, in fairness to even the platinum-bonded crown, these can often be made thinner than you could a fused porcelain-to-metal crown.

In premolars we build an alumina core as a miniature tooth. But if aluminous porcelain is used it can be made fairly translucent by presintering the material and fritting it to a molten glass-crystal mixture where it is much more homogeneous. Reasonable translucencies can be produced so that the veneering porcelains do not have to be quite so thick. This is another possibility, and miniaturizing of the tooth should not be ignored as an alternative to using a coping. If you do not reinforce the marginal ridges, even with the current special ceramic* coping, a break will occur at the marginal ridge of unsupported porcelain. Even with metal, clinical experience shows you have problems if you do not reinforce marginal ridges.

The platinum-foil technique allows the technician to withdraw and eliminate undercuts. If there is an undercut on the die he can at least eliminate it during construction.

The reason fracture with platinum bonding occurs in the fossae or marginal ridge areas is due to high stress as determined by El-Ebrashi, Craig and Peyton¹⁰ in their classical stress analysis studies. These areas must remain of greatest concern when constructing the complete ceramic restoration. Dr. B. D. Arbeid, a London practitioner, has made hundreds of posterior platinum-bonded crowns.¹¹ He flattens the occlusal table to give a thicker layer of core porcelain. For the first 4 yr he was having no problems, but at 6 to 7 yr he is starting to get fractures, illustrating the importance of long-term clinical testing. That is why metal is so hard to beat; it is a tough material.

If metal is compared to even high alumina with about 500 MPa (70–80 000 psi) flexural strength, this value is near the yield point of the metal, not the ultimate tensile strength. In summary, until the strength of ceramics are in this area, bridgework will remain a very, very dangerous procedure. The tensile strength of high alumina compared to porcelain is good at 4:1, the impact strength ratio is 8:1, and modulus ratio is 4:1. These are large increases in strength and this is what is needed if they are to replace metal.

How could ceramics be developed for fixed bridgework without metal? Clearly one could consider using Coors nonshrink ceramic in which high-alumina rod reinforcement could be incorporated. Preformed high alumina of strength equivalent to metal to connect up the bridge areas can be made, but the coping and pontic area must be reinforced with a material of really high strength. This presents a problem, because even with aluminous porcelain breaks occurred. The break was invariably in the weaker section, which would

be the alumina core. The same conditions would apply to the special ceramic,* or even to glass-ceramic. Care must be taken with the supporting occlusal platforms that are going to give (and of course the connector areas). These are the areas where very high strength is essential. This is precisely why metal castings, designed for use with fused porcelain, must support the occlusal platforms of the porcelain. If you do not support the occlusal platforms, breaks will occur in pontic areas, and marginal ridges (Fig. 2). A clean break could even take place through the actual connector area.

There are critical areas where stress is at its maximum in any high-strength alumina-ceramic bridge. It is very difficult to get adequate cross-sectional areas in all portions, particularly as you move up from the embrasure space into the main body area of the crown. This is the region where they fail and is precisely why metal is so advantageous.

In this meeting Starling will give a masterly survey of the special ceramic;* they are utilizing a 325-mesh and fine alumina powder ($<10\ \mu\text{m}$) as the reinforcement. By using a mixed oxide of magnesia and aluminum, they can form a magnesium aluminate spinel which reduces shrinkage. My technicians have had only limited experience with the system but have not had any great problem with the transfer molding which is fairly straightforward. The firing cycle is comparatively long, and we find that when the top temperatures are reached, problems in controlling fit result. The restorations are usually too tight or they may be over expanded. However, with further experience it appears that these problems can be overcome; but the question must be posed that if a ceramic material is produced with a certain volume porosity in the green material, and is also dependent upon constituents to control shrinkage, can the firing cycle ensure exact compensation for shrinkage in all cases, irrespective of the design of the coping? The second factor is, of course, strength. With the magnesium aluminate spinel, the flexural strength of the special ceramic* is about 120 MPa, which is far below that of high alumina porcelain. This flexural strength may not be high enough for molars to survive over a long period if the occlusal thickness is below 1.5 mm. Unfortunately, it is not always possible to have a 1.5 mm section occlusally. The safe value for flexural strength is about 400 MPa. Major concerns are therefore (1) control of shrinkage, and (2) the low flexural strength, particularly for posterior teeth or bridgework. Otherwise, the material should be quite successful. The technique is not difficult although it is time consuming and cost-wise at the moment my technicians are of the opinion it is more costly than using metal.

In the future, ceramic copings or miniaturized ceramic teeth, which are simply veneered, is the direction in which to move in order to get the best out of high-strength ceramics. Increases in the cross-sectional area of the core porcelain are imperative, and if possible it should be more translucent.

Glass-ceramics have a lot of potential because of their ease of fabrication. They can be cast, but the problems that McCullough¹ observed in 1968 have not gone away. The main problem is that if a glass-ceramic is cast and ceramed, it is monochromatic. It cannot be made in layers and requires surface staining or veneering with porcelain to produce the color of the natural tooth. However, there is no doubt that this is a beautiful and sophisticated system for dispersion-strengthening. It can be crystallized in situ and the crystal size can be controlled for strength. It can be cast using the lost wax process by heating the glass in the crucible and has many of the advantages of metal. The material

is very appealing and easy to handle. If you look at the system of investing and centrifugal casting, it is similar to what the laboratory technician is familiar. However, consistency of casting is only in the 95% range, but even when casting gold alloys, a 100% success rate is not easily achieved. The fit of the cast-glass restoration is good, and the exact shape and size is obtained by the lost-wax process. The glass casting can then be ceramed to achieve the color. The problem is the final color because this has to be done by surface staining as originally described by McCullouch.¹ The color may be adequate for posterior teeth since some sort of gradation between cervical, body and incisal color would be possible. However, with front teeth, technicians who are building metal-ceramic work or pure jackets are using the most sophisticated layering techniques and building enamel with a lateral segmental technique. Enamel cracks, differences of translucency, and all the inner defects that you see in a human tooth can be simulated. If you look at the work of Geller of Switzerland, Yamamoto and Kuwata of Japan, Kedge in England and your own technicians in the United States, the best dental technicians are producing the most intricate color systems. They can only do it by hand-building the porcelain veneers which, of course, restricts the use of the glass-ceramic until they develop methods of layering color. For example, they could make a miniature tooth in glass-ceramic over which the technician could hand-veneer the colors. I believe that glass ceramics can be developed that have strengths of about 300 MPa, which is not quite high enough, but certainly in the right direction. The finished result after surface staining looks quite acceptable, but in five yr time this stain may disappear. It is now generally recognized that surface staining on ceramics does tend to disappear with the years and built-in color is preferred.

Q. You were speaking in terms of 15% failure for your ceramic molar crowns. Did you retrospectively determine then what your occlusal thickness was for these failures?

A. No. In a busy practice like mine it was not possible to measure every occlusal thickness. The only thing I can tell you is I checked all the ones that broke and they were invariably less than 1 mm at the central fossa.

Q Very good. Did you examine them to determine the source of fracture?

A. Do you mean from the point of view of opposing cusps?

Q. Well, not necessarily. Where, within the crown, did the fracture originate?

A. This is not an easy thing to judge. I would say it was breaking from central fossa outwards.

Q. On the outer surface, or the fitting surface?

A. Well, again if you are bonded to platinum you will generally get a break occurring somewhere within the structure of the ceramic which goes clean through the platinum and the ceramic. In fact, it breaks the platinum simultaneously. We were very interested in the fact that when bonding to platinum with tin oxide coatings, if it does break, it tends to break the ceramic and the platinum simultaneously. You get a little bit of tearing obviously, but you do not get a piece of ceramic breaking off the platinum. It goes through the platinum. Now you can make a conjecture exactly how the fracture started. I would say in most situations it would not break from the outside in, because the outside would be under too much compression. Therefore, I would think that most of those failures occurred somewhere within a pore which was close to the interface and then they break out.

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*Cerestore, Ceramco Inc., East Windsor, NJ.

[†]Lucalox, GE, Schenectady, NY.

[‡]Vita-Dur, Vitazahnfabrik, H. Rauter GmbH & Co. KG, Bad Sackingen, West Germany.

[§]Vita-Pt, Vitazahnfabrik.

Table I. Results of Clinical Testing of Bonded Platinum Aluminous Porcelain Crowns*

Year	Total No. crowns					No. of failures**			
		Molars	Pre-molars	Canines	Incisors	Molars	Pre-molars	Canines	Incisors
1974	93	13	21	9	50	3	3	—	—
1975	112	26	20	11	55	5	1	—	2
1976	102	11	19	9	63	1	1	—	2
1977	109	1	18	14	76	—	—	—	1
1978	121	8	27	17	69	—	2	1	2
1979	82	—	11	10	61	—	1	—	2
1980	60	—	9	7	44	—	—	—	—
Total	679	59	125	77	418	9	8	1	9
Failure (per cent)						15.2	6.4	1.3	2.1

*See Ref. 12.

**Failure includes chipping or complete fracture.

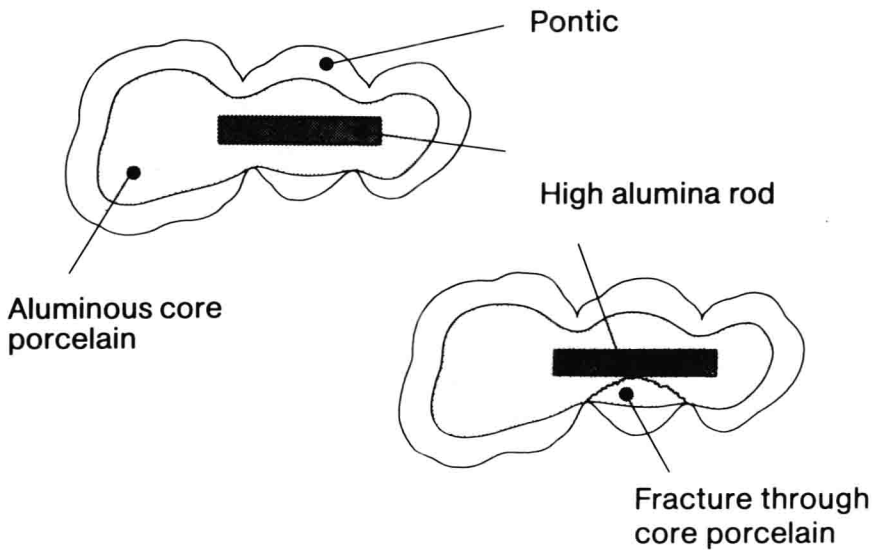


Fig. 1. The potential sites of fracture in the occlusal table of an all-porcelain bridge made with alumina reinforced rods. (Reprinted by permission, Copyright 1983. Quintessence Publishing Co.).

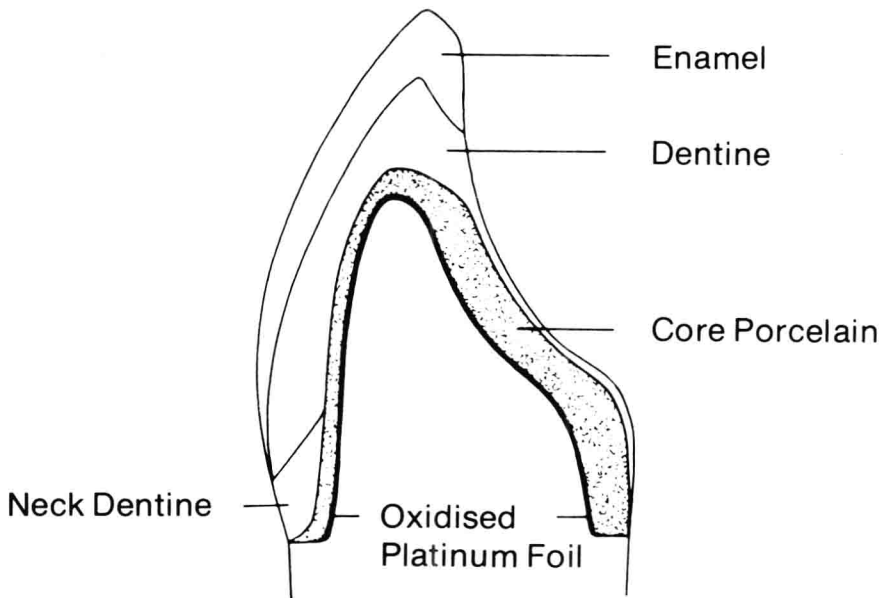


Fig. 2. A cross section through a bonded alumina crown. (From Ref. 2. Reprinted by permission, Copyright 1979. Quintessence Publishing Co.).

High Expansion Feldspar Porcelain and Magnesia Core Materials

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Feldspar porcelains have been used in dentistry for denture teeth since the early 1800s and more recently as veneering for crown and bridgework. Porcelains for veneering metal substructures have higher thermal expansion values due to an increase in leucite content. Recently high expansion magnesia ceramics have been developed which serve as an inner core reinforcement for the construction of all ceramic crowns. The construction of a feldspar crown is done by hand using finely ground factory-fritted porcelains and firing to produce vitreous sintering.

Introduction

Dental porcelains are composed of feldspar glasses along with pigment mill additions. High expansion porcelain enamels have a higher leucite content and are used to construct porcelain-fused-to-metal crown and bridgework.¹ Dental crowns are made by forming the anatomy with a paste followed by vitreous sintering. Porcelain-to-metal bond failures are of great concern and have been studied extensively.²

Dental porcelains are translucent ceramics which simulate the appearance of natural teeth. Porcelain denture teeth have been used since the 18th century but have been gradually replaced by acrylic teeth. The application of porcelain to restore individual teeth as small inlays and full crowns became widespread in the late 1800s with the development of small dental laboratory porcelain ovens by Dr. Charles Land.³ Dental porcelain has many characteristics which make it superior as a restorative material. It has a glossy, white, tooth-like appearance and a translucency which simulates that of natural tooth structure. It is also inert and highly resistant to absorption of liquids and staining. Its main disadvantage is brittleness and low strength. Although used for many years as a material for porcelain crowns, its use has accelerated with the development of porcelain-fused-to-metal crown and bridgework. The introduction of high expansion porcelains which could be bonded to gold and nickel alloys took place in the late 1950s. Recently several improvements in the all porcelain crown have also been introduced: strong ceramics for use as reinforcement cores, injection-molded ceramic core materials, and cast glasses which are heat treated to form strong ceramics. The main emphasis in this paper will be on the feldspar porcelain systems because of the widespread use of these materials in crown and bridge.

Feldspar Porcelains

Feldspar porcelains are classified as whitewares according to the relative amounts of feldspar, silica, and kaolin used as raw materials. Only denture teeth porcelains contain kaolin, a type of clay, because it improves the molding properties of the mass made by mixing with water prior to packing in metal molds for firing. Orthoclase feldspar is mainly potassium aluminum silicate

(KAlSi_3O_8) and used in the manufacture of most dental porcelains because of its resistance to flow during firing. Soda feldspar, or albite, consists of sodium aluminum silicate and forms porcelains with lower viscosity values. When feldspar is mixed with alkali metal carbonates and heated to around 1000°C it forms mainly a glass and a crystalline phase known as leucite. Leucite has a high coefficient of thermal expansion and is the basis for the high-expansion porcelains used with metals for porcelain-fused-to-metal crown and bridgework. A glass is an amorphous, irregular structure produced by large alkali metal ions. Sodium, potassium, and lithium distort the crystal structure of silica which is formed by the breakdown of feldspar during heating. These glasses flow at lower temperatures than silica which makes the densification of dental porcelain possible at 870° to 1300°C . Dental porcelains are classified according to their fusion temperature which is the temperature at which sufficient glass is melted to form a glossy layer on the surface known as a glaze. The three types are high-fusing (which is 1288° – 1371°C), medium-fusing (which is 1093° – 1260°C), and low-fusing (which is 871° – 1066°C). The older porcelain crowns, known as jacket crowns, were made with high-fusing feldspar porcelains. The porcelains for fusion to metal are low-fusing porcelains in order to avoid melting of the metal substructure. The most widely used crown and bridge porcelain fuses at 980°C (1800°F). In order to match the shades of teeth, dental porcelains are supplied in kits containing around a dozen formulations of different “shades” or tooth colors. Each porcelain crown is also composed of porcelains of three different levels of translucency as shown in Fig. 1. The most translucent layer is called the “enamel” or “incisal” porcelain. The body porcelain makes up the bulk of the crown and has a lower translucency. The inner layer of porcelain is opaque and covers the underlying metal surface. In the case of an all-ceramic jacket crown, the opaque porcelain is replaced by an inner core material. The basic composition limits of the white porcelains used for bonding with metals are given in Table I. The silica content is mainly responsible for the acid resistance of the porcelain. The alkali metal content lowers the fusion temperature of the porcelain but increases the solubility of the porcelain. The alumina content increases the viscosity of the porcelain. Oxides such as tin oxide, titanium oxide, and zirconium oxide are added as opacifiers and mechanically mixed with the ground white porcelain to reduce the translucency. Opaque porcelains contain 10–15% of these white oxides. Natural tooth shades are produced by the addition of small amounts of colored oxides to give yellow, pink, blue, and gray tints to the white porcelain. The oxides of cobalt, iron, chromium, and complex ceramics known as spinels are used as pigments. Glazes are low-fusing glasses which are fired on the surface of porcelain to give a glossy appearance. Since glazes contain high concentrations of alkali metals and boric oxides, they are high in solubility and may wear off in service. Therefore, the natural glaze produced by fusion of the glass from within the porcelain which then flows to the surface is considered preferable. Stains are glazes which contain high concentrations of the coloring pigments found in porcelain. They are used to modify the colors of the basic shades found in a porcelain kit. However, they also wear off with time and their use is questionable, but expedient in matching existing teeth.

Processing

Dental crowns are made from dental porcelain by what is known as the build-up technique. The powder is mixed with water or a liquid containing

glycerine and other additives to form a paste. This paste is then painted on the alloy crown substructure or platinum foil matrix which has been swaged over the die of the tooth and dried by a process called condensation. Condensation consists of the removal of excess water from the porcelain-liquid paste and may involve the use of vibration and blotting with paper. As each layer of the crown is applied and condensed, it is then fired before application of the next layer. The process of densification by firing dental porcelain is sintering. During sintering, the glass of the porcelain flows sufficiently to cause coalescence of the individual particles of the porcelain.⁴ Complete fusion of the porcelain is prevented in order to retain the anatomical form of the crown. Sintering is dependent upon surface tension of the glass, the viscosity of the glass at the firing temperature, the firing temperature, and the time. Therefore, sintering can be carried out faster at a higher temperature since the viscosity of the glass is lower. Particle size is another factor with small particles sintering faster. Changes in the particle size distribution of a porcelain strongly affect the rate of sintering. There are at least three stages in the sintering of porcelains. The first stage is called the bisque bake and is the initial stage of sintering in which sufficient sintering has taken place to develop some cohesion. The high bisque-bake stage involves the flow of additional glass and increase in strength. The final stage is known as glazing. This stage involves the flow of glass to the surface of the ceramic. The glass flows to the surface from within the ceramic and forms a layer which gives the porcelain a glossy appearance. Usually this glazing can be seen through a window in the furnace oven and ceramists will heat a crown just to the point of glazing. During sintering porcelain shrinks around 15% in length. In the case of denture teeth, oversized molds are used to fire denture teeth to compensate for the shrinkage. In firing crowns, the initial shape is oversized and additional porcelain is added in subsequent bakes. If the crown does not match the desired tooth shade at the final bake, a stain in a glaze is often applied to alter the color.

Properties

Since porcelains contain a considerable amount of glass, the thermal expansion of porcelain follows the behavior of glasses. The thermal expansion curves of the major dental porcelains for bonding to metals are shown in Fig. 2. It can be seen that there is little relationship between expansion and temperature until the glass transition temperature is reached. Above the glass transition temperature the rate of expansion increases. As the porcelain is heated further it reaches the softening temperature. In the range of the temperatures around the glass transition temperature we find the annealing range. If a porcelain is annealed in this range, stresses are relieved due to a flow of the glass. Below the annealing range the glass is too rigid for the release of stresses. The values for the coefficient of thermal expansion of porcelain enamels is between $13\text{--}14 \times 10^{-6}/^{\circ}\text{C}$ which is in the same range as that of the alloys used to cast substructures for crown and bridgework. Older jacket crown porcelains have values around $6\text{--}8 \times 10^{-6}/^{\circ}\text{C}$.

Strength Properties

Porcelains are brittle with total elongation values less than 0.1%. They are much weaker in tension or transverse loading than in compression. Strength values of porcelains for bonding to metals are given in Table II. Here we can see that the tensile strength is considerably lower than that of the compressive