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Bond strength between a silica glass-fiber-reinforced composite and artificial polymer teeth

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Abstract
Objective. A resin-bonded prosthesis is preferred when conservation of abutment tooth structure is required, although a problem with such systems is bonding between the fixed partial denture material and a polymer pontic. The aim of this study was to investigate the bond strength of a silica glass-fiber-reinforced composite to polymer teeth compared with the bond strength of a proprietary heat-polymerized denture base polymer and also between a layer of the polymerized matrix polymer of the experimental base material and an additional layer of the same material. ***Material and methods.*** Polymeric artificial maxillary incisors and two heat-polymerized base materials (ProBase Hot and an experimental formulation) were used. Three test groups (each $n = 6$) were prepared: bonding between artificial tooth and an experimental composite (group-TC), bonding between tooth and ProBase Hot (group-TP), and bonding between experimental base material and experimental base material (group-BB). The content of inorganic particles of teeth was determined by combustion analysis. The bond strengths were measured in shear with a universal testing machine and the data were analyzed by one-way ANOVA and post-hoc Scheffé test ($p < 0.05$). After failure, the fracture surfaces were examined by optical microscopy. ***Results.*** The content of inorganic particles in the teeth was low. There is no statistically significant difference in bond strength between the groups. ***Conclusions.*** Bond strength of the experimental composite to artificial polymer teeth was as good as that of a conventional heat-polymerized denture base polymer. The strong bonding between the experimental material and artificial teeth makes this combination suitable for resin-bonded prostheses.

Key Words: *FRC framework, heat-polymerized resin, pontic, resin-bonded prosthesis*

Introduction

Resin-bonded prosthesis is one of the treatment options for replacing a tooth when minimal preparation of abutment tooth structure is desired [1–5]. A resin-bonded prosthesis with a cast metal framework was first described by Rochette [6], but because of the high cost of the metal framework, frequent debonding of restoration and lack of esthetics (such as the color of the cast metal frame), new materials have been introduced [7]. With the improvements in adhesive dentistry, fiber-reinforced composites (FRCs) have become widely used in dental applications such as resin-bonded FRC prosthesis [1–5,8,9].

Studies of resin-bonded FRC prostheses indicate good clinical performance in short-term clinical use, such as provisional restorations during the healing time of implant treatment [10] and replacement of single teeth in young patients as a lead-up to implant therapy at a later age [2]. It has been reported that the overall survival rate of resin-bonded, glass fiber-reinforced composite fixed partial dentures with a mean follow-up of 42 months is 75%; the 25% failure due to “debonding and FRC fractures” [1].

FRC fixed partial dentures can be prepared either directly chair-side [9] or indirectly in the dental laboratory [1]. With an appropriate indirect method, the prosthesis has superior esthetics, surface polish, color stability and durability compared to the direct method [2].

Resin-bonded FRC prostheses have recently been presented with a substructure composed of fiber bundles pre-impregnated with a resin matrix and a particulate filler composite (PFC) that covers the FRC substructure for preparation of the pontic [3,11]. The clinical failures of restorations with the FRC framework and PFC reported in the literature

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have mostly been delamination or debonding of PFC from the underlying FRC framework [12].

Using a proprietary artificial polymer tooth pontic with a fiber-reinforced polymeric framework structure can be an alternative method to the FRC framework with a composite pontic in the preparation of indirect resin-bonded FRC prostheses. Factors affecting the attachment of teeth to the base material are: laboratory technique, composition of the materials [13], and the compatibility between artificial tooth and base material [14]. Heat-polymerized resins produce higher bond strengths than visible light-polymerized resins [13]. Proprietary polymer teeth have the ability to bond to the denture base polymers because of diffusion of the monomers of the denture base polymer into the polymer teeth during heat polymerization [15,16]. For auto-polymerized denture base polymers, bond strength increases with increasing polymerization temperatures. Correspondingly, the bonding characteristics were changed from adhesive to cohesive failure [16].

However, light-polymerized systems based on dimethacrylate monomers do not seem capable of satisfactory bonding [17,18]. In one evaluation of the effect of shear bond strength of FRC to tooth structure, fiber reinforcement did not appear to improve bond strength significantly [19].

Detachment is caused by stress concentration in the vicinity of the tooth/denture base polymer interface [20]. A number of national and international specifications describe methods for determining the bond strength between denture bases and polymer teeth [18]. According to the International Organization for Standardization (ISO) [21,22], the bond is deemed satisfactory (strong bonding) if the fracture is cohesive within the polymer tooth and/or the denture base polymer.

During clinical use, fractures can be seen in restorations probably due to intra-oral mechanical, thermal and hydrolytic loading. In order to avoid expensive replacement of an entire restoration with a new one, repairs may be preferred, and auto-polymerized, heat-polymerized, or visible light-polymerized resins can be used [23,24]. Successful denture repair is reliant on the phenomenon of adhesion, and strong bonding of the surfaces improves the strength of the repaired unit and reduces stress concentration [25].

Silica glass-fiber-reinforced polymer frameworks can be used for the preparation of resin-bonded FRC prostheses. The physicochemical properties, e.g. improved hydrolytic stability compared with E-glass-fiber composites, have been described previously [26–28]. Such a modified poly(methyl methacrylate) (PMMA)-based resin system remains in a fluid state, i.e. dough stage during storage and handling, until polymerization [29]. Laboratory studies have shown that both polymer matrices and silica-glass FRCs have good flexural properties [26,27,29].

The hypothesis of the present study was that the addition of silica glass fibers and the incorporation of poly(vinyl chloride-co-vinyl acetate) within the resin matrix should not reduce the bonding properties. To test the hypothesis, the aim was to evaluate bond strength by shear bond testing [17,20,30] the experimental silica glass-fiber-reinforced polymer framework [27,28] to polymer teeth compared with a representative system of a proprietary heat-polymerized denture base material and polymer teeth; moreover, to evaluate the possibility to repair the experimental base material.

Material and methods

An experimental and a proprietary heat-polymerized denture base material (ProBase Hot; Ivoclar Vivadent AG, Schaan, Liechtenstein) were used in this study. The experimental material was prepared as described previously [29]. The experimental resin was based on methyl methacrylate, poly(methyl methacrylate), poly(vinyl chloride-co-vinyl acetate) and diethylene glycol dimethacrylate [29]. The proprietary one was based on methyl methacrylate, dimethacrylate monomer and poly(methyl methacrylate). Maxillary incisors (SR Vivodent; Ivoclar AG, Schaan, Liechtenstein) were selected as the artificial teeth.

Three test groups with six specimens for each group were prepared as follows (Figure 1): (i) Group-TC. Artificial tooth and silica glass-fiber-reinforced experimental base material; (ii) Group-TP. Artificial tooth and ProBase Hot; and (iii) Group-BB. Experimental base material and the same prepolymerized experimental base material.

Determination of filler content

The content of inorganic fillers in the artificial tooth was determined, as described previously, by combustion of three tooth samples at 575±25°C for 60 min [26].

Preparation of test specimens

The specimens were prepared in four stages: Preparation of the samples with wax, polymerization of mounting polymer, preparation of bonding surfaces, and preparation of the final samples.

Preparation of the samples with wax

For groups TC and TP, the artificial tooth was placed within an orthorhombic wax block (Tenax Wax; SS White, Gloucester, England) prepared with the dimensions 21.0±0.2 mm, 11.0±0.2 mm, 6.0±0.2 mm, and for group BB, a wax block of the same

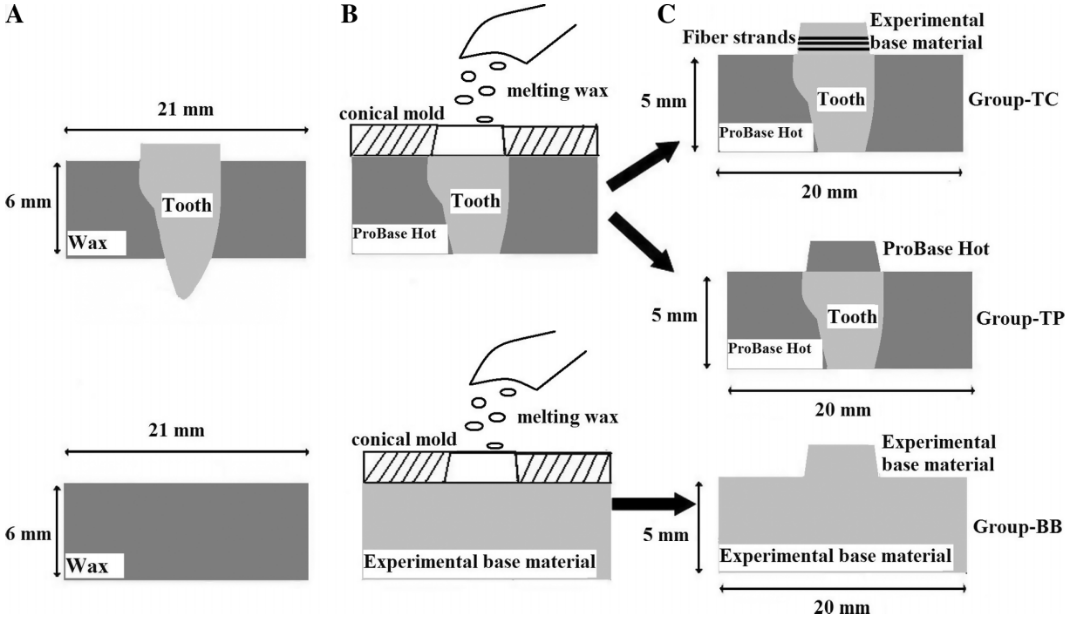

Figure 1. Schematic drawing of test samples. A. Wax samples. B. Conical mold contact with polymerized samples. C. Final samples.

dimensions without tooth (Figure 1A). The blocks were measured by digital micrometer (Mitutoyo Digimatic Micrometer; Mitutoyo, Kawasaki, Japan; standard measurement uncertainty 0.001 mm). Afterwards, either the tooth-wax sample or the wax-only sample was placed in a denture flask with gypsum (Moldabaster S, Heraeus Kulzer Engineering Inc, Buffalo, NY, USA), and when set, the wax was flushed with boiling water. For preparation of samples in the TC and TP groups, ProBase Hot was filled into the mold for mounting the teeth, and for samples in the BB group, the experimental base material was filled into the mold.

Polymerization of mounting polymer

ProBase Hot was polymerized in accordance with the manufacturer's instructions. The mold was placed in water and heated to 100°C maintained for 45 min. For the experimental base material, the mold was placed in water and heated to 70°C maintained for 90 min, when the temperature was increased to 100°C and kept at this temperature for 1 h. Both procedures included bench cooling to room temperature.

Preparation of bonding surfaces

After polymerization and cooling, the samples were removed from the mold and ground with P500 (30 μm) and P1200 (15.3 μm) silicon carbide paper [31] (Struers A/S, Ballerup, Denmark) to final dimensions of $20 \times 10 \times 5$ mm. The bonding surfaces of the samples were then abraded with P2400 (8 μm) silicon carbide paper.

Preparation of the final samples

A slightly conical stainless steel mold [32], 2.50 ± 0.05 mm in height with a larger diameter of 5.0 ± 0.1 mm and 4.9 ± 0.1 mm at the narrower end, was used to produce the final samples. The wider end of the conical mold was put into contact either with the tooth or with the prepolymerized experimental polymer block (Figure 1B). The wax was melted and poured into the conical hole. After cooling, the wax and an orthorhombic specimen were carefully removed from the conical mold. The orthorhombic specimens with the conical wax model were placed in a denture flask with dental gypsum. When the gypsum had set, the wax was removed and the mold was filled with one of the three materials: experimental base material with strands of 2.1 vol% unidirectional silica glass fibers 5.0 ± 0.2 mm in length, ProBase Hot and experimental base material without fibers. The fiber strands were placed parallel to the interface and in the direction of the shearing force during the later bond test.

The fibers used in the study had been acid-washed, heat-treated at 500°C, silanized, and sized with a solution of butyl methacrylate (BMA) and linear poly(butyl methacrylate) (PBMA) [27]. The unidirectional fibers (Quartzel, Saint-Gobain Quartz, Nemours Cedex, France) consisted of >99.99 wt% fused silicon dioxide. According to the manufacturer, the physical and mechanical properties of silica fiber filaments have a tensile strength of 6000 MPa; tensile modulus 78 GPa; elongation at fracture 7.7%; density 2.2 g cm^{-3} and diameter 9–14 μm.

After polymerization and flask cooling, the completed samples (Figure 1C) were removed from the gypsum. The excess resin flash at the bonding site

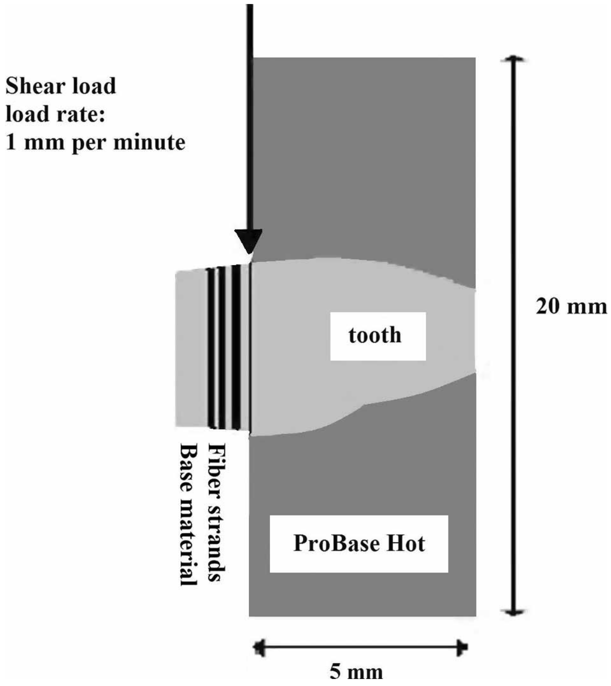

Figure 2. Schematic illustration showing fiber-reinforced base material on tooth for shear bond testing.

was removed to ensure that the strength measurements represented only the tooth–denture base interface bond. The samples were stored at 23 ± 1°C and 50 ± 5% relative humidity for 7 days.

Shear test

The area of the joint surface, or adhesive surface area (S), was determined using the mean diameter of two diameter measurements at right angles to one another. The apparatus for testing shear bond strength [32] consisted of a solid block for holding the specimen and a vertical shearing blade with an edge of thickness 0.30 ± 0.02 mm at a distance 0.50 ± 0.02 mm from the surface of the metal plate. The specimen was adjusted and fixed for shear testing, and all tests were performed on a Universal testing machine (Lloyd LRX, Lloyd Instruments, Hampshire, England) using a cross-head speed of 1 mm min^{-1} (Figure 2), and the load F at fracture was recorded. All tests were performed at 23 ± 1°C and 50 ± 5% relative humidity. Bond strength (B) was calculated from the equation $B = F/S$, where F was the load in N at fracture and S the adhesive surface area in mm^2.

Microscopic examination

After failure of samples, the fracture surfaces were observed with a Photo Makroskop Wild M400 (Wild Heerbrugg, Heerbrug, Switzerland).

Statistical analysis

Mean and standard deviations (SD) were calculated for each group of specimens. The results of the measurements in the three different groups were investigated by one-way ANOVA and post-hoc Scheffé test using a statistical software package (Statistical Package for the Social Sciences for Windows, v. 15.0.1; SPSS, Chicago, Ill., USA). The level of significance was set at 0.05.

Results

Filler content

The mean (SD) content of inorganic particles of the artificial teeth was measured gravimetrically to be 2.1 (0.3) wt% after combustion.

Shear test

The mean (SD) bond strengths (MPa) of the three test groups were 17.5 (1.6) (Group-TC), 18.9 (1.8) (Group-TP) and 20.5 (1.7) (Group-BB). There was no statistically significant difference between the bond strengths of the test groups.

Microscopic examination

After the shear test, only cohesive failures were observed at the fracture surfaces (Figure 3). Three failure modes were observed: (i) Cohesive fracture within the tooth (Figure 3A); (ii) cohesive fracture within the base material (Figure 3B, C); and (iii) cohesive fracture within both tooth and base materials (Figure 3D).

Number of samples and cohesive fractures for each group were evaluated. In Group-TC, one sample had a fracture within tooth, four samples had fractures within base material and one sample had a fracture within both tooth and base material. In Group-TP, four samples had a fracture within tooth and two had a fracture within both tooth and base material. In Group-BB, all samples had a fracture within the orthorhombic block base material.

Discussion

The use of FRC in resin-bonded prosthesis has been suggested because of better adhesion of the composite luting agent to the FRC framework than to the metal framework, good esthetics and physiological stiffness of the framework material [3]. A combination of silica glass FRC framework and an artificial tooth can be used as an alternative method to the commonly used production methods for resin-bonded prosthesis. The present study was designed

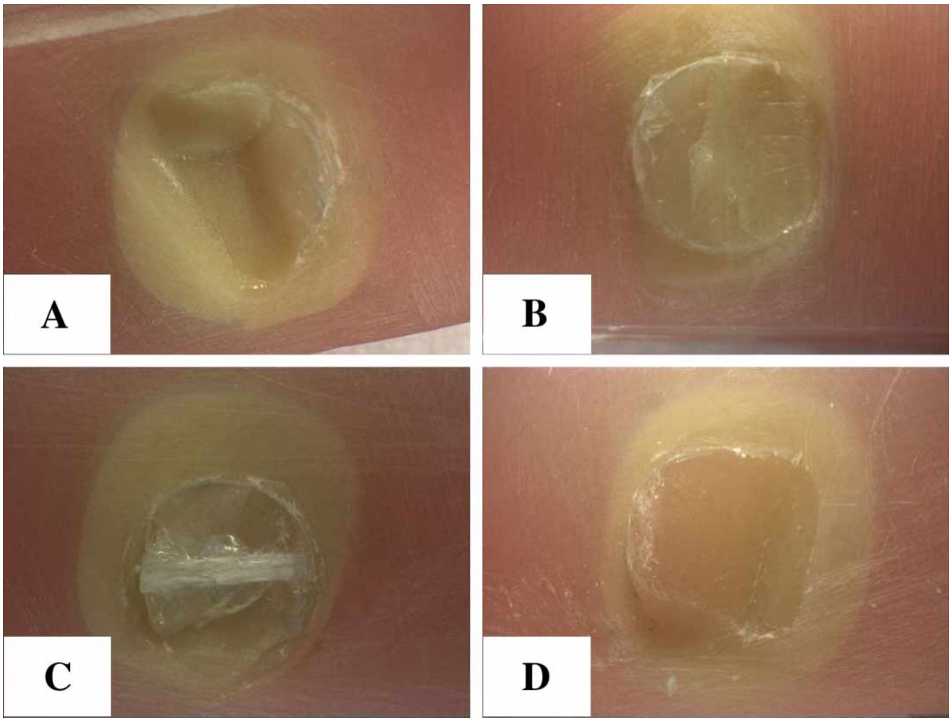

Figure 3. Types of bonding failure. A. Cohesive fracture within tooth. B. Cohesive fracture within experimental base material. C. Cohesive fracture within experimental base material along fiber bundles in same direction as shear loading. D. Cohesive fracture within both tooth and ProBase Hot.

to show that the bond strength of a recently developed silica glass-fiber-reinforced composite framework to artificial teeth is as good as the bond strength of a conventional heat-polymerized denture base polymer to polymer tooth. The bond strength of the experimental base material was also evaluated for possible repairs.

Acrylic resin and polymer teeth heat-polymerized at 100°C resulted in high bond strength [15,16]. In the present study, the upper processing temperature applied for both ProBase Hot and the experimental base material was 100°C.

The good bonding properties in all three test groups can be explained by the presence of methyl methacrylate in the base materials [15,16,26]. This monomer has good swelling properties towards the polymer teeth owing to diffusion of the monomer from the base resins into the teeth polymer [15]. At the elevated temperature of up to 100°C, a substantial depth of penetration of the monomer methyl methacrylate and the cross-linking dimethacrylate monomer is obtained and in the penetrated region an interpenetrating polymer network (IPN) is formed resulting in the good bond strength values [15].

Properties of FRCs depend on the direction of the force applied relative to the fiber orientation. It has been concluded that the highest shear bond strength values of PFC to FRC were obtained when the fibers were oriented perpendicular to the bonding surface [30]. However, in the present study the fibers in the samples were oriented parallel to the shear stresses. Even though the fibers placed close to the bonding surface did not improve the bond strength, they could act as a crack-impeding component [19]. Another function of these parallel orientated unidirectional fibers could be reducing the polymerization shrinkage at the bonding surface between tooth and FRCs.

Cohesive fracture was observed for all specimens in the present study. These findings were thus in accordance with international standards for artificial teeth and denture base polymer for dental prostheses [21,22]. The pattern of fracture may provide some information about shear strength, e.g. four specimens of group-TC had a fracture in the FRC, whereas four specimens of group-TP had a fracture in the polymer tooth. This could indicate that in such a system ProBase Hot has better shear resistance than FRC.

The good bonding strength of the experimental base material to the same prepolymerized experimental base material indicated that the base material can be used for possible repairs. Repair of the restorations with the heat-polymerized resins is not easy and is time-consuming. However, the increase in temperature of polymerization improves mechanical and chemical properties of acrylic resin [16]. For instance, heat-polymerized acrylic resins are stronger than auto-polymerized materials. The repair strength of auto-polymerized acrylic resins has been shown to be 60% of the original material and that of heat-polymerized materials 80% [23]. Auto-polymerized resins demonstrate higher transverse strengths than visible light-polymerized resins when used in the repair of heat polymerized resins [24].

The strength of the bond is related to the composition of the materials and laboratory technique. Owing to the low inorganic filler content of the polymer teeth used in the present study, they are regarded as non-composite teeth. Büyükyilmaz & Ruyter [16] have shown that the mean (SD) bond strength of ProBase Hot polymerized at 100°C and a polymer tooth is 25.3 (0.8) MPa. The results of the present study indicate that the mean (SD) bond strength of Pro Base Hot polymerized at the same temperature and a polymer tooth is 18.9 (1.8) MPa. The difference can be due to the different properties of the teeth fabricated by different manufacturers, but the more likely reason is the different polymerization procedure. In the present study, there was a gradual heating to 100°C, whereas the reported bond strength [16] was obtained by a halt at 70°C for 30 min and further heating to 100°C maintained for 30 min.

Conclusions

Within the limitations of this study, the following conclusions can be drawn. Despite the different composition of the resin with a copolymer of poly(vinyl chloride-co-vinyl acetate) and the addition of silica glass fibers, there was no statistically significant difference between the bond strengths for polymer tooth-experimental composite and polymer tooth-ProBase Hot, both commonly used proprietary polymeric prosthetic systems. The results from this study and from previous studies indicate that silica glass-fiber-reinforced composites can be used for resin-bonded prostheses.

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