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On the design of dental resin-based composites: A micromechanical approach

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Abstract

Adhesive resin-based restorative materials have the potential to considerably strengthen teeth and offer more economically viable alternatives to traditional materials such as gold, amalgam or ceramics. Other advantages are direct and immediate placement and the elimination of the use of mercury. However, polymerization shrinkage during curing of an adhesive restoration and mismatch in mechanical properties can lead to the initiation and development of interfacial defects. These defects could have a detrimental effect on the longevity of the restored tooth. The current study is focused on some design issues of resin-based composites affecting the longevity of the tooth–restoration interface. The theoretical approach is based on self-consistent micromechanical modelling that takes into account the effect of the material properties, volume concentration of the dispersed particle phase as well as the shape of these particles on the overall thermomechanical properties of the composite. Results obtained for resin-based composites reinforced with spherical, disc and short fibre particles highlight the advantages of disc shaped and short fibre particles.

Keywords: Dental resin-based composites; Design; Interfacial failure; Polymerization shrinkage; Micromechanics

1. Introduction

1.1. Adhesive resin-based composite restorations

Currently, adhesively retained resin-based composite restorations based on polymeric resins often reinforced with inorganic particles or chopped fibres are employed to a large extent in contemporary restorative dentistry [1,2]. There has been considerable development of these adhesive resins over the past 10 years, which are considered as alternatives to traditional metal- and ceramic-based dental restorations. A prominent advantage of these composite restorative materials is their ability to bond to tooth structure. Among the other advantages are better aesthetics, avoidance of mercury, reduced fracture susceptibility, as well as the potential for a more conservative cavity preparation with less reliance on mechanical retention. The advent of adhesive dentistry, particularly bonding to dentine, increases the strength and stiffness of the tooth and thereby reduces fracture susceptibility.

However, two significant disadvantages of these composite materials are polymerization contraction and the mismatch in mechanical properties with tooth structure [3]. Polymerization shrinkage during the curing reaction is typically in the range of 2.6–7.1% [4]. The shrinkage stresses that develop during curing of an adhesive restoration can lead to the initiation and development of interfacial defects [5]. These defects could have a detrimental effect on the longevity of the restored tooth and have been associated with clinical symptoms such as micro-leakage, post-operative sensitivity and microbacterial contamination with associated secondary caries. It is possible to reduce the volumetric shrinkage by adding inorganic particles to the resin, which also results in an increase in the viscosity of the composite prior to curing and an increase in

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stiffness. However, increased stiffness is normally associated with higher polymerization stresses and the combined effect can be deleterious.

Another common failure mechanism of teeth restored with traditional restorative materials as well as with resin-based composites is delayed fracture. It is believed that the high stress concentrations due to the mismatch of thermomechanical properties of the restorative materials relative to the tooth structure plays an important role in creating conditions for micro-crack initiation. Recent studies have demonstrated micro-cracking and crack propagation in dentine [6,7]. As fractures become apparent many years after the placement of the restoration, the mechanism of delayed fracture is thought to be cyclic fatigue where the crack in dentine propagates in small increments in response to the occlusal load, eventually leading to complete tooth failure [8,9]. Kruzic et al. showed via in vitro experimentation that crack propagation in dentine is due to cyclic fatigue damage as an end result of subcritical cracking induced by repetitive occlusal stresses rather than a succession of static fracture events [7]. The difference in the thermal expansion coefficients of the restorative material and human dentine can result in even higher stresses than occur under masticatory and para-functional loading and also can be considered as a primary source of the fatigue damage [10].

1.2. Composition

The physical, mechanical and aesthetic properties as well as the clinical handling properties are dependent on the composition of resin composites. The majority of dental resin composites are hybrid materials consisting of polymer groups that are reinforced by an inorganic phase of glass fillers which may have different compositions, particle sizes and filler percentages. In simplified terms, dental resin composites are derived from three chemically different materials: (i) the organic matrix or organic phase; (ii) filler or disperse phase; and (iii) an organosilane or coupling agent to bond the filler particles to the organic matrix. The filler particles improve some physical and mechanical properties of the organic matrix by reducing shrinkage and the thermal expansion coefficient [11], increasing fracture toughness and flexural strength [12–15] as well as improving the handling properties [16].

Filler particles vary considerably in respect of their chemical composition, morphology and dimensions. Lutz and Phillips classified composite resins according to the filler particle size: (i) macrofiller composites with particles from 0.1 to 100 μm; (ii) microfiller composites with particle sizes of 40 nm; and (iii) hybrid composites with variable filler sizes typically ranging from 0.6 to 1 μm and containing 40 nm sized colloidal silica [17]. More recently, nanotechnology has led to the development of a new category of resin composites containing nanoparticles measuring approximately 25 nm and nanoaggregates of approximately 75 nm [11]. The addition of fibres has also been shown to improve mechanical properties [18,19]. Williems et al. proposed a classification based on a number of parameters, including Young's modulus, the percentage (by volume) of inorganic filler, and the size of the main particles, surface roughness and compressive strength [20].

Fine particle composites contain ground glass or quartz particles occupying 60–77% of the composite by volume and 70–90% by weight. Particles present may be uniform or variable in diameter. Microfine composites contain spherical colloidal silica particles 10–120 nm in diameter with an average surface area of 200 $m^2 g^{-1}$, which greatly increases the viscosity of the polymer matrix upon incorporation. Filler loading is as a consequence limited to 20–55% by volume or 35–60% by weight. Filler content can be increased by grinding a polymerized microfine composite into particles 10–20 μm in diameter and combining these reinforced particles with colloidal silica. Heavily filled microfine composites have a filler content of 32–66% by volume or 40–80% by weight. Hybrids have a combination of colloidal and fine particles as filler with a volume content of 60–65% [1].

The mechanical properties of resin composites are dependent on the filler component with many studies reporting relationships between fillers and flexural strength [21–23], compressive strength [24], diametral tensile strength [25,26], transverse strength [13], shear punch strength [27], fracture toughness [15], hardness [28], wear [29], shrinkage stress [30] and thermal expansion [31].

To increase the longevity of dental restorations the development of new restorative materials such as resin-based composites must consider their thermomechanical properties, in particularly polymerization shrinkage and the mismatch in thermomechanical properties. Unfortunately, as discussed above, it is practically impossible to vary one mechanical characteristic and, at the same time, keep others unchanged. Consequently, physical and mathematical models of failure mechanisms, such as those developed in Kahler et al., are required to achieve a compromise between the competing failure mechanisms to ensure the optimal performance of the restoration [10,32]. If this compromise between failure mechanisms is to be found for a particular class of restoration, then a design procedure is necessary to select materials, volume ratios and the shape of the particles to develop the specified or desired material properties. The current paper is focused on this design procedure. A micromechanical approach based on mean-field theory will be presented next to give a practical guide to the selection process.

2. Micromechanical approach

The proportion of fillers can be expressed by weight or by volume ratio. In resin-based composites, the volume ratio of inorganic fillers generally ranges between 35% and 80% of the composite [33]. The effect of the filler particles on polymerization shrinkage is dependent on the type, shape, size, volume fraction and the effective coupling between the filler and resin matrix [34]. Roughly, three large groups

ID	Title	Pages
1982	On the design of dental resin-based composites: A micromechanical approach	8