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Visualization of Marginal Integrity of Resin-Enamel Interface by Holographic Interferometry

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Clinical Relevance

Holographic interferometry offers precise insight into both the frequency and location of cohesive fractures through its fringe information. If flowable composites are not used as a first layer, fringe distribution indicates cohesive fractures as a consequence of composite polymerization.

SUMMARY

This study determined whether it was possible to detect deformations and fractures in dental hard tissues or in composite material from internal stresses using double-exposure holographic interferometry. On the proximal side of eight intact human permanent premolars, a direct Class II cavity was prepared and restored with a self-etching adhesive (Clearfil SE Bond) and Tetric Ceram, a resin composite. In five of the specimens, Tetric Flow was used as an elastic layer. The samples were illuminated using a helium-neon laser beam, and the holograms of samples were recorded using Agfa 10E75 photographic plates. Hologram reconstructions were captured with an 8-bit monochrome CCD camera and qualitatively analyzed. Deformations and fractures appeared as fringe patterns on all interferograms, where the distribution of fringes provided location information, while the density of fringes gave the amplitude information. Greater fringe densities were observed in samples treated without a flowable composite.

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INTRODUCTION

Polymerization shrinkage represents one of the main problems in the use of composite materials.[1] Shrinkage appears at the start of polymerization, when monomer molecules in the composite form polymer chains. As a

consequence, the volume of the resin composite generally decreases. There are numerous methods for determining polymerization shrinkage: dilatometry (mercury or water dilatometry), linometer, measuring of specific density and weight of the material, the "strain-gauge" method, the "deflecting discs" method and other methods.[2-5] In a recent study, a digital interferometry device was used to measure thickness variations of resin composite samples during blue light polymerization.[6-7]

Many factors influence the quality of the polymerization reaction.[3,8] For instance, the size of the monomer molecules; the speed with which the polymerization reaction begins; the size, type and amount of inorganic filler particles; the intensity of light and the time of exposure and distance of the light source from the resin composite.

Movement and the spatial organization of monomers are responsible for the change in volume during polymerization.[9] The formation of macromolecules during radical polymerization implies compression or loss of volume. *In vitro* measurements show composite materials exhibit linear shrinkage of 0.2% to 2% and volume shrinkage of 1.7% to 5.7%, with an intermolecular distance of 0.3 nm to 0.4 nm between monomers. A covalent bond of 0.15 nm, established during polymerization, causes shrinkage of the polymerized composite material.[10]

At the start of polymerization, the organic matrix is in a viscose plastic state, which enables flow and allows the monomers to move or fall into another position. As the polymerization process continues, larger molecules form and the resin composite hardens. The material takes a rigid elastic form but still shrinks. When shrinkage stops, stress appears.

The loss of volume at the beginning of polymerization is compensated for by flow of the resin composite from free to bonded surfaces. Stress at the joining areas between the hard dental tissue and restorative material will not be significant with regard to compensation. As polymerization continues, the resin composite hardens, and compensation by "flow" can no longer counteract the shrinkage. At that moment, new forces appear along the joining surface between the restorative material and the tooth, causing tension or "stress." Those forces pull the composite material off the cavity walls. Conversion of the material into a hard state causes further shrinkage of the material, and the stress continues to elevate. If the stress exceeds bond strength, the bond integrity is broken by leakage or formation of an adhesive fracture that compensates for the loss of volume and decreases total stress.[11]

If the bond strength is stronger than stress, the loss of volume caused by shrinkage can be compensated for in a different manner: either by exertion onto the surrounding structures or by deformation of the material and the creation of cohesive fractures (Cf) inside the material and/or hard dental tissues. It has been concluded that permanent stress on the bond surface threatens long-term stability of the marginal integrity between the tooth and the composite material.[12]

Shrinkage stress is not solely connected to composite shrinkage. A strong correlation exists between stress and the modulus of elasticity of the composite material.[13] The modulus of elasticity and the amount of inorganic filler greatly influence the degree and maximal amount of stress caused by shrinkage.[14]

Other factors that influence stress include the geometric form of the cavity, the application technique and characteristics of the restorative material and tooth structure.[15]

The total amount of stress and its direction in the resin composite is influenced by the light source intensity and illumination time, position and distance from the light source, composite layer thickness, composite reactivity, radio-opacity, color of the composite and modulus of elasticity.[3,16]

For several years, the quality of composite materials has been tested by measuring the degree of conversion with other mechanical tests.[17-18] As early as 1975, Jorgensen, Asmussen and Shimokobe observed marginal microleakage on the areas parallel to the bond surface, which is caused by contraction of the composite material.[19] Staninec and others have indicated that microleakage is a consequence of several combined factors: polymerization shrinkage of the restorative material, heat contraction, water absorption, mechanical stress and dimensional changes of the hard dental tissue.[20] Roulet also observed Cf of the filling and enamel margins.[21] Oberländer, Friedl and Schmalz stated that fractures formed in dentin are mostly adhesive, while fractures formed in enamel are both cohesive and adhesive. Cohesive fractures form mostly in composite material.[22]

According to Van Dijken, Horstedt and Waeren, cervical enamel fractures appear in 5.6% of cases, while, according to Malmström and others, enamel fractures occur in 28.3% of cases.[23-24]

Characteristics of Cf have still not been researched and described in detail. Holographic interferometry is a method that could offer precise insight into both the frequency and area of composite fractures.

Holography is a two-stage method that stores information about the object wave front, then later reconstructs it. The wave front information, consisting of the amplitude and phase parts, is recorded using fine-grained photo material. Since all photo materials are sensitive to light intensity, it is necessary to transfer information about phase with an intensity variance.

This transfer can be accomplished by recording interference of the wave from the object surface and reference wave. When the photo record develops, a hologram is obtained as a two-dimensional distribution of light and dark fringes (primary fringes). Visibility of the primary fringes depends on light coherency, optical system stability, differences in optical pathways and similar parameters. The recorded wave front is reconstructed by diffracting the reference wave on the hologram.

Holographic interferometry is based on comparing two object wave fronts. The double-exposure method provides information about the differences between two object states. This process is realized experimentally by recording two holograms on the same photo plate, then reconstructing the two mutually interfering object wave fronts. As a result of the interference, the fringe pattern is obtained, which shows the location and amplitude of deformations created between two exposures of the object surface. For additional information on the status between or after the second exposure, it is necessary to make a new interferogram. Method sensitivity usually varies between λ/10 (minimum detectable fringe value) and 100 λ (maximum detectable fringe value), where λ represents the wavelength of light.[25] In recent applications, holograms have been recorded using CCD sensors instead of photo plates.[26]

METHODS AND MATERIALS

Recording holograms (the first stage) is shown schematically in Figure 1a, while the reconstruction stage is presented in Figure 1b. The photograph of the system is shown in Figure 2. The whole system is composed of an He-Ne laser, a beam shutter, a beam splitter, an object carrier, a photographic plate carrier, mirrors, lenses, a CCD sensor and a computer.

The interferograms (double-exposed holograms) were recorded by the following experimental procedure:

1) Preparing and positioning the sample.
2) Positioning the photographic plate.
3) Exposing the photo plate (the first exposure).
4) Covering the photo plate.
5) Reconstructing the crown cavities (photopolymerization).
6) Exposing the photographic plate (second exposure).
7) Developing the photo plate (obtaining a double-exposure hologram).
8) Reconstructing the hologram (obtaining object wavefront + interferometric fringes).
9) Recording and analyzing the obtained reconstructed image.

On eight intact premolars extracted for orthodontic reasons, direct Class II cavities were prepared. The chosen group was selected randomly; the selection criteria was that the teeth be completely intact and one-rooted. Whether the teeth were upper or lower premolars was not considered, because the purpose of the study was to present a new method for showing microcracks, not determining whether microcracks appear more often on the upper or lower premolars. It was important that all random edges of the cavity remain in enamel; therefore, the teeth that satisfied the size criteria were selected.

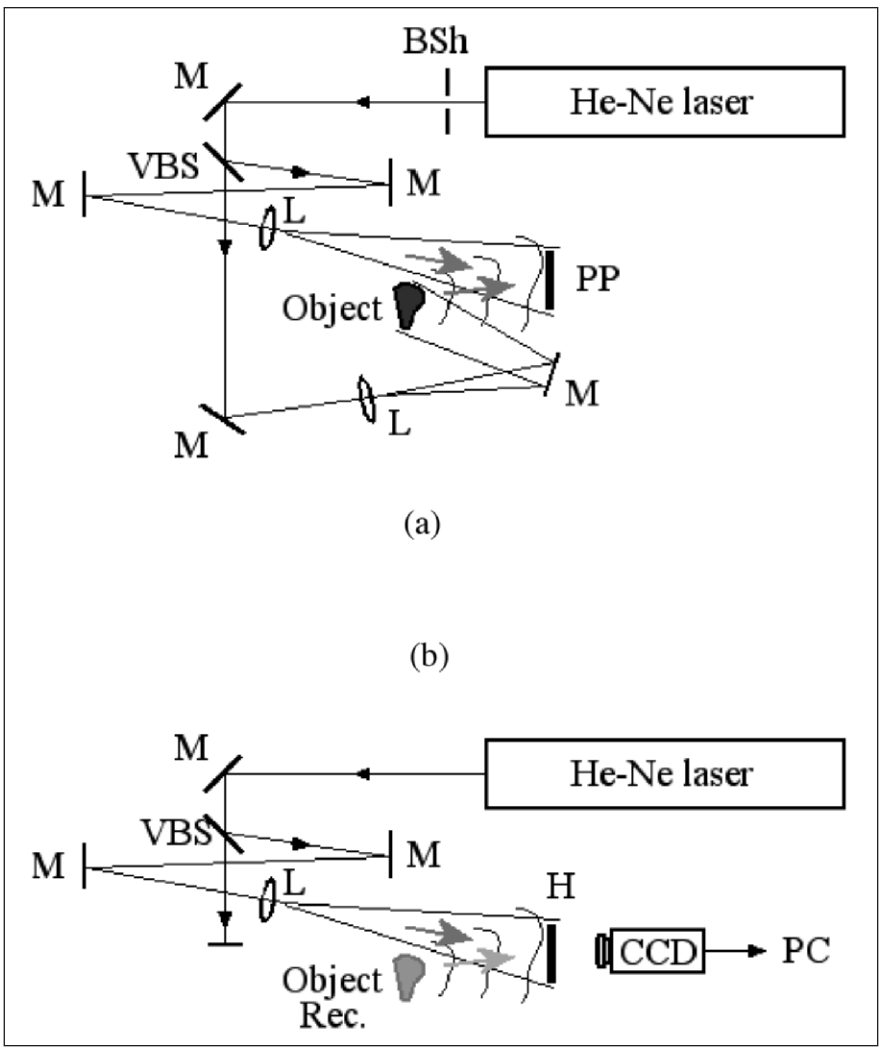

Figure 1. *Scheme of the experimental setup: a) hologram recording, b) hologram reconstruction. BSh–beam shutter, VBS–variable beam splitter, PP–photographic plate, H–hologram, M–mirror and L–lenses.*

For preparation of all proximal cavities, a diamond burr was used (8801.314.035 and 69.09.314.040 [Comet GmbH, Garbsen, Germany]) with a diameter of 4 mm, so that all cavities had approximately the same size. The deepest part of each cavity was in the center. The edges were placed in enamel and beveled at a 45° angle with a diamond burr (645.204.420 [Comet GmbH]).

Each molar was placed and firmly fixed in the holder of the holographic setup. It was important for the sample to be fixed firmly, because any movement would ruin the primary fringe recording and thus degrade the object reconstruction field. An He-Ne laser (λ=632.8 nm), with an outgoing power of 25 mW and Agfa 10E75 photographic plates, were used. The laser beam was first split into two beams by a variable beam splitter: the object beam and the reference beam. The reference beam was expanded and steered using mirrors directly onto the photographic plate. The object beam was first expanded, collimated and steered onto a mirror situated on the upper surface of the sample, then reflected with a small angle to the photo plate. The interference of the beams was recorded using the CCD sensor (CCD camera with objective lens removed) with 752×582 pixels that were 8.6×8.3 μm each.

Figure 2: *Photograph of the holographic setup.*

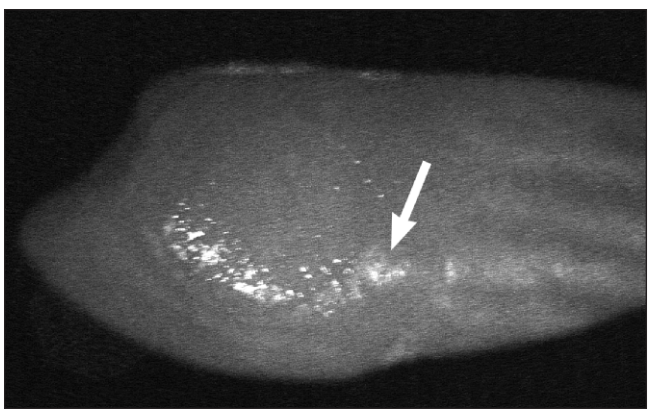

Figure 3a: *Holographic image of hybrid composite filling with flowable resin composite. *Arrows point to interferometric fringes that show fractures in the enamel edges.*

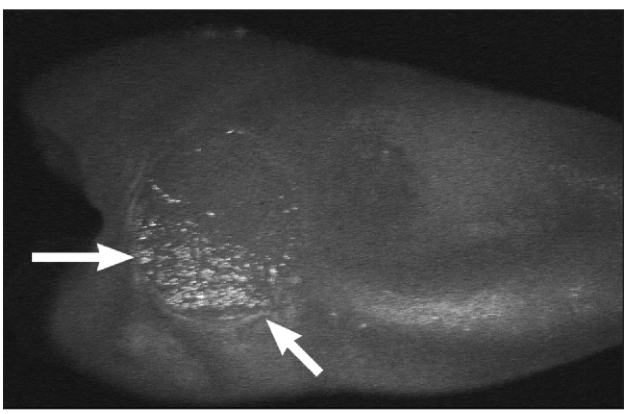

Figure 3b: *Holographic image of hybrid composite filling with flowable resin composite. *Arrows point to interferometric fringes that show fractures in the enamel edges.*

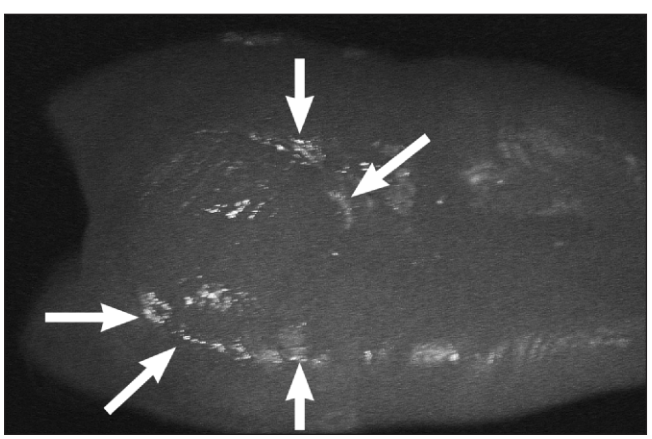

Figure 4a: *Holographic image of hybrid composite filling without flowable resin composite. *Arrows point to interferometric fringes that show fractures in the enamel edges.*

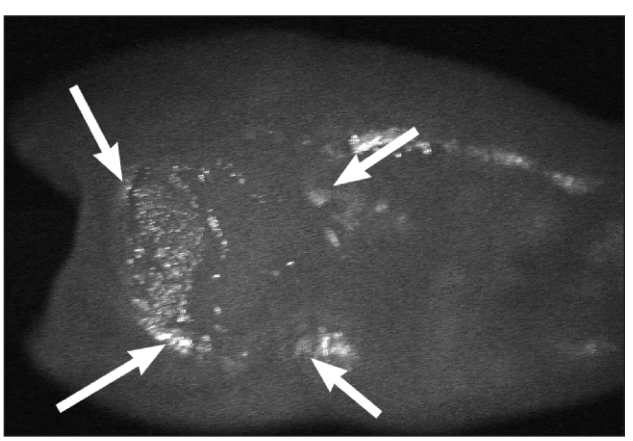

Figure 4b: *Holographic image of hybrid composite filling without flowable resin composite. *Arrows point to interferometric fringes that show fractures in the enamel edges.*

After the first exposure, each tooth was prepared for filling placement. The self-etch adhesive (Clearfil SE Bond, Kurraray, Osaka, Japan) was used according to the manufacturer's instructions. After polymerizing the adhesive for 20 seconds with the "pulse" mode of the Astralis 10 halogen curing unit (Vivadent, Schaan, Liechtenstein), a 1 mm thick layer of flow composite (Tetric Flow, Vivadent, Schaan, Liechtenstein) was placed in four specimens. After polymerizing the flow composite for 40 seconds, Tetric Ceram (Vivadent) was placed in two oblique layers, with each layer being polymerized separately for 40 seconds.

Another four premolars were reconstructed with the self-etch adhesive Clearfil SE Bond (20 second polymerization) and hybrid composite Tetric Ceram (40 second polymerization per layer).

The analysis of two-dimensional reconstructed images can generally be qualitative or quantitative. Qualitative analysis explains object changes by identifying positions of microcracks, defects in composite surface and tooth deformation. Quantitative analysis is more demanding and requires determining the exact defect location, direction and counting of the fringes. Numerical processing enables better accuracy for obtaining results, which can then be related to the distribution of stress within the material.

RESULTS

The reconstructed images were analyzed qualitatively. The results are shown in Figures 3a, 3b, 4a and 4b. A greater number of microcracks and a greater density of fringes in marginal interface between resin composite and enamel were noticed on the images of samples without flowable resin composite (Figures 4a and 4b) than on the samples where flow composite was used (Figures 3a and 3b). This can be concluded due to the greater number and density of interferometric fringes.

DISCUSSION

Microleakage in the enamel margin of the restoration that appears immediately after polymerization was observed by Prati and others.[27] Staninec and others provided the explanation for fracture formation.[20] Polymerization shrinkage causes dimensional changes of the material in the form of thermal contraction, water absorption and dimensional changes of the tooth structure, all which contribute to the formation of fractures in enamel. Resistance to acid is reduced in non-prismatic enamel, rather than in prismatic enamel. Greater bond strength can be established for transversally cut enamel than for longitudinally cut enamel. Additionally, enamel cut perpendicular to the direction of the prisms provides a greater bond strength than does enamel that has been cut parallel to the prisms.[28]

Enamel fractures were first observed by Shimida and others and Carvalho and others.[28-29] Manhart, Cehn and Hickel observed enamel fractures on restoration margins.[30] Most enamel fractures are located in the zone of parallel prisms. As margins of the restoration in this study were not beveled, the assumption was that fractures were formed as a result of an unfavorable angle of enamel prisms cross section. Similar observations were made by other studies.[19,28,31] This group of authors think that areas of parallel prisms are more susceptible to acidic conditioner action, which often causes the formation of large, demineralized areas where hydroxyapatite crystals remain unsupported. Such areas in enamel are less resistant and easier to fracture when subjected to forces caused by polymerization contraction.

Fractures in the cervical area were described by Van Dijken and others in 5.6% of the samples, while Malström and others found fractures in 28.3% of the samples.[23-24] Fractures of the hard dental tissue appear to be a consequence of shrinkage of the composite material during polymerization. The amount of stress at the joining surface is dependent on the modulus of elasticity of the composite material. Rigidity and elasticity modulus are inversely related. As rigidity increases, so does stress; therefore, if the surrounding structures are not sufficiently elastic, something will break to compensate for the loss of volume.[32] In an attempt to solve this problem, flow composites were created by decreasing the amount of inorganic filler.[1] As a result, viscosity of the composite increased but so did polymerization shrinkage. In order to decrease polymerization stress without influencing the physical properties of the material, the use of a thin layer of material with a low elasticity modulus and low viscosity, which would act as a shock-absorber, has been suggested.[24] Using this method can decrease the polymerization contraction value by 20% to 50%,[33] as demonstrated by the results of Leevailoj and others.[12]

There are opposing views in the current literature regarding the efficiency of flowing composite materials as shock absorbers. Recent studies have stated that materials with a low modulus of elasticity can absorb polymerization shrinkage stress but that the flowing composites available on the market are too rigid and do not affect the generated stress.[34-36] This opinion is held by Choi, Condon and Ferracane and Hilton and Quinn.[32,37]

Suliman, Boyer and Lakes noticed movement and tension in enamel after polymerization.[38] A decrease in tension and cusp deflection due to the application of flow composites was confirmed by Alomari, Reinhardt and Boyer and Rooklidge, Boyer and Bouschlicher, who reached the same conclusion.[10,39]

In this study, examination of the surface by holographic interferometry was conducted by the visual

interpretation of density and localization of the fringes.[40] Fringes were observed on the crown of all samples. A large number of fringes located on the composite surface is evidence for the molecular movement of monomers during the pre-gel phase. In both sample types, fringes visible on the root of the tooth indicate the spreading of polymerization-induced stress. Fringe distribution is influenced by the number of roots and root canals. A greater density of fringes on the root of the sample treated without flowable composite was noticed.

In this study, the holographic approach is demonstrated for the first time. The use of holographic interferometry shows advantages in detecting all relevant changes on the tooth surface as influenced by the polymerization process.

CONCLUSIONS

The holographic interferometry method indicates, with great precision, changes and deformations caused by polymerization stress and shrinkage on the observed tooth surface. Greater density of interferometric fringes was observed on holographic images, where flowing composite was not used. This indicates a sizeable degree of change of the surfaces observed in those samples. Additional study and a corresponding computer program are needed to perform quantitative analysis of the samples.

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