DENTAL MATERIALS 25 (2009) 582–588

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.intl.elsevierhealth.com/journals/dema

# Measurement of the full-field polymerization shrinkage and depth of cure of dental composites using digital image correlation

*Jianying Li*[a], *Alex S.L. Fok*[a,*], *Julian Satterthwaite*[b], *David C. Watts*[b]

[a] *Minnesota Dental Research Centre for Biomaterials and Biomechanics, University of Minnesota, USA*
[b] *School of Dentistry, University of Manchester, UK*

ARTICLE INFO

*Article history:*
Received 12 September 2008
Received in revised form
31 October 2008
Accepted 1 November 2008

*Keywords:*
Image correlation
Dental composite
Polymerization shrinkage
Depth of cure

ABSTRACT

*Objectives.* The aim of this study was to measure the full-field polymerization shrinkage of dental composites using optical image correlation method.
*Methods.* Bar specimens of cross-section 4 mm × 2 mm and length 10 mm approximately were light cured with two irradiances, 450 mW/cm$^2$ and 180 mW/cm$^2$, respectively. The curing light was generated with Optilux 501 (Kerr) and the two different irradiances were achieved by adjusting the distance between the light tip and the specimen. A single-camera 2D measuring system was used to record the deformation of the composite specimen for 30 min at a frequency of 0.1 Hz. The specimen surface under observation was sprayed with paint to produce sufficient contrast to allow tracking of individual points on the surface. The curing light was applied to one end of the specimen for 40 s during which the painted surface was fully covered. After curing, the cover was removed immediately so that deformation of the painted surface could be recorded by the camera. The images were then analyzed with specialist software and the volumetric shrinkage determined along the beam length.
*Results.* A typical shrinkage strain field obtained on a specimen surface was highly non-uniform, even at positions of constant distance from the irradiation surface, indicating possible heterogeneity in material composition and shrinkage behavior in the composite. The maximum volumetric shrinkage strain of ∼1.5% occurred at a subsurface distance of about 1 mm, instead of at the irradiation surface. After reaching its peak value, the shrinkage strain then gradually decreased with increasing distance along the beam length, before leveling off to a value of approximately 0.2% at a distance of 4–5 mm. The maximum volumetric shrinkage obtained agreed well with the value of 1.6% reported by the manufacturer for the composite examined in this work. Using irradiance of 180 mW/cm$^2$ resulted in only slightly less polymerization shrinkage than using irradiance of 450 mW/cm$^2$.
*Significance.* Compared to the other measurement methods, the image correlation method is capable of producing full-field information about the polymerization shrinkage behavior of dental composites.



* *Corresponding author at*: Minnesota Dental Research Centre for Biomaterials and Biomechanics, School of Dentistry, University of Minnesota, 16-212 Moos Tower, 515 Delaware Street SE, Minneapolis, MN 55455, USA. Tel.: +1 612 625 0950; fax: +1 612 626 1484.
E-mail address: alexfok@umn.edu (A.S.L. Fok).
0109-5641/$ – see front matter 
doi:10.1016/j.dental.2008.11.001

## 1. Introduction

Resin-based dental composites are now widely used for dental restoration because of their good properties and aesthetic appearance. However, polymerization shrinkage of the polymer-based materials is of concern as the resulting shrinkage stresses can lead to failure of the interfacial bonds, which results in marginal leakage, premature failure of the restoration, and in some cases micro-cracking of the tooth [1,2]. Therefore, the search for low (or even no) shrinkage in the material during resin polymerization has long been a goal in the development and manufacture of dental composites.

In parallel, a number of methods for measuring the polymerization shrinkage of dental composites have been devised. Among them, dilatometry, which is based on Archimedes' principle, is commonly used for measuring volumetric shrinkage. Using this method, a composite sample is immersed into a bath of mercury or water, and the variation of the liquid level during polymerization of the composite is recorded [3]. The bonded disc method is another method which can measure the volumetric shrinkage of dental composites to a good approximation. With this method, a thin disc of the dental composite is bonded to a rigid lower glass plate while a thin piece of glass diaphragm is bonded to the top surface of the composite disc. The deflection of the diaphragm caused by the shrinking composite during polymerization is then measured using a linear voltage differential transducer (LVDT) [4]. There are variants of this method which use a laser interferometer or optical magnifier to measure the polymerization shrinkage [5–7]. Linear shrinkage, on the other hand, can be measured using the non-bonded disc method [8]. Here, a lubricant is applied between the lower base plate and the composite disc, thereby allowing the latter to shrink freely without constraints. Other investigators have used mechanical strain gauges to measure the so-called post-gel shrinkage strain when the composite has developed significant stiffness and stresses to cause deformation in the strain gauges [9,10]. Most of these methods have been discussed and compared in the literature [11,12].

All the shrinkage measuring methods described above can be classified as contact measurement methods because the composite sample is in direct contact with either a liquid or solid medium: mercury or water in dilatometry, a glass diaphragm and a LVDT in the bonded or non-bonded disc method, and a strain gauge in the strain gauge method. Through gravitational and/or adhesive forces, the medium in contact with the composite may exert loads and/or constraints to it, giving rise to other forms of deformation and hence influence in the measurement of the polymerization shrinkage.

Non-contact shrinkage measurements have been carried out by other investigators using laser beam scanning or video-imaging techniques [13,14]. With these techniques, the external dimensions of the composite specimen are monitored or recorded continuously, and by determining its overall shape change during the polymerization process the average material shrinkage can be obtained. More recently, 3D micro-CT imaging techniques have been used to measure polymerization shrinkage of dental composites [15]. However, the method is currently limited for measuring the final overall shrinkage.

Digital image correlation is another non-contact optical method which is often used to measure the flow of fluid [16] and the surface strain distribution in materials testing [17], etc. In this study, this technique was adopted to measure the polymerization shrinkage of dental composites. During polymerization, a series of images of the specimen are taken using a CCD camera and the movements of individual spots on the surface of the specimen are tracked and analyzed using specialist software to determine their displacements. The strains can then be derived from the displacement fields. Compared with the other measuring methods including the video-imaging method, a feature of this method is that, instead of just the overall shrinkage, full-field shrinkage strains showing local details can be obtained for the whole surface of the specimen under observation. Therefore, the polymerization shrinkage of the dental composite at different distances from the irradiation surface can be measured with this method, from which the depth of cure can also be established. In addition, the composite sample does not have to be in direct contact with a rigid medium that would provide significant constraint.

With increasing distance from the irradiation surface, the degree of conversion (DC) of the composite material will decrease [18]. Such a variation in DC with subsurface distance is due to the attenuating effects of absorption and dispersion of the curing light as it passes through the material. The depth of cure is important clinically as it affects the mechanical properties of the composite restoration. Incomplete polymerization of the dental composite will lead to low hardness, excessive wear, low strength and low marginal retention [19,20]. Besides the degree of conversion, variation in the material's hardness, as measured by indentation, and that of shrinkage can also be used as an indicator of the depth of cure [19,21]. Indeed, the three parameters are interrelated as they all result from the same polymerization process. However, the mapping of DC and hardness as a function of distance and time are relatively laborious.

This paper reports the measurement of polymerization shrinkage and its variation with subsurface distances of dental composites using digital image correlation. The aim of the work was to evaluate the effectiveness of the method and the accuracy of the measurements thus obtained.

## 2. Materials and methods

### 2.1. *Specimen preparation and experimental instruments*

The dental composite used in this investigation was Premise Dentin (shade A3, batch number 32731), manufactured by Kerr. It is a universal nanofilled composite, with 69% filler load by volume. Volumetric shrinkage of this material is reported to be 1.4–1.91% by the manufacturer (Kerr Dental Materials Center) and other research facilities [22,23].

The composite material was placed into a mould to form rectangular-sectioned (4 mm × 2 mm) bars (see Fig. 1). The length of the bars was approximately 10 mm. The mould was