# Polymerization shrinkage and stress analysis during dental restoration observed by digital image correlation method

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## 1. Introduction

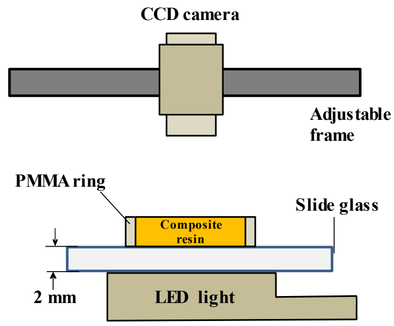
Polymerization shrinkage of dental composite resins occurs due to covalent bonding of the monomers in the polymerization reaction. The resin shrinkage creates a tensile stress in the restoration. Interfacial defects are caused by the tensile stress occurring between the composite resin part and tooth substrate. The Interfacial defects would form secondary caries and tooth fracture, which can significantly reduce restored tooth life [1, 2] and lead to hyper-sensitivity in patients who underwent dental restoration treatment. However, existing studies have rarely been analyzed by observing the polymerization shrinkage behavior of the resin curing process with time from the start of light irradiation.

In this study, two types of composite resin were used for the test of restoration. Digital image correlation (DIC) method is applied for the observation of shrinkage deformation behavior of the resins for dental restoration during and after light irradiation. The strain distribution results by DIC are converted to the principal stress distribution characteristics utilizing an equivalent modulus of elasticity [3].

## 2. Methods

**2.1 Dental Restoration and Digital Image Correlation Analysis :** Filtek P90 (3M ESPE, USA) and AP-X (Kuraray, Japan) dental resins with significantly different shrinkage strains are used for the test of restoration. A ring type substrate was used to measure polymerization shrinkage behaviors of the composite resins. The ring substrate with 6 mm outer diameter, 4 mm inner diameter, and 2 mm height was made of polymethylmethacrylate (PMMA).

Through DIC, the deformation behavior was calculated by comparing the images of surface stain patterns before and after deformation based on the random pattern of the material surface [4]. As illustrated in Fig. 1, digital images of polymerization shrinkage distribution were measured using the DIC camera system (ARAMIS 2M LT, GOM, Germany). The light irradiation was conducted at an intensity of 1000 W for 20 s. Because the intensity of LED light during light irradiation and the intensity of indoor lighting after light irradiation were drastically different, the optimal shooting condition for each case was measured through preliminary tests.



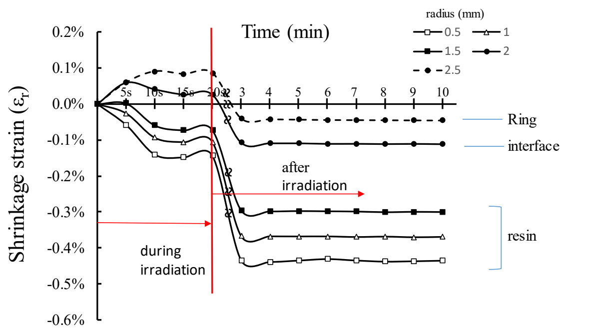

**2.2 Finite Element Stress Analysis :** The principal stress distribution on the surface of the specimen was calculated on the basis of the three-dimensional FEM. As illustrated in Table. 1, an equivalent elastic modulus was obtained beforehand [3] for the composite resin subjected to the entire curing process, and it was applied to the FEM model.

Table 1. Material properties of composite resins and PMMA ring used for FE calculation.

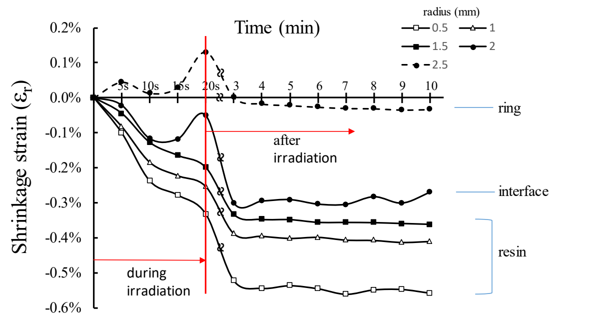
| Properties | Filtek P90 | | Clearfil AP-X | | PMMA |
|---|---|---|---|---|---|
| | Resin | Bond | resin | Bond | |
| Elastic modulus [MPa] | 153 (equivalent) | 2300 | 186 (equivalent) | 4400 | 3200 |
| Poisson's ratio | 0.3 | 0.3 | 0.26 | 0.24 | 0.3 |
| Polymerization Shrinkage [vol.%] | – 0.88 | - | – 1.9 | - | - |

## 3. Results and Discussion

Fig. 2 shows average radial shrinkage strain ($\bar{\varepsilon}_r$) measured for each radius location r according to the elapsed time from the start of light irradiation. For the resins of P90 (Fig. 2a) and AP-X (Fig. 2b), $\bar{\varepsilon}_r$ significantly decreased as the location of radius moved from around the center of the resin (r = 0.5 mm) to the margin (r = 2.0 mm). For P90, natural shrinkage was approximated at 46% of that of AP-X. However average shrinkage strain was –0.14% at r = 0.5 mm just before the end of light irradiation for 20 s, and it was rather expanded to +0.08% at r = 2.5 mm in the substrate ring due to heat received from the light source and by the exothermal polymerization reaction. At ~3 min after the irradiation, the polymerization shrinkage deformation was shown as almost completed. At the end of the curing test at 10 min, $\bar{\varepsilon}_r$ was at the maximum to be –0.43% at r = 0.5 mm, exhibiting a peak shrinkage, whereas it was very low to be around –0.04% at r = 2.5 mm. The average of $\varepsilon_r$ near the interface after the curing test was about 2.5 times higher in AP-X than P90 (Fig. 2), which was almost consistent with the shrinkage strain behavior of the resins themselves provided by the manufacturer (Table 1), in that AP-X was approximately twice as high as P90. However, the average radial shrinkage strain around the center of the resin (r = 0.5 mm) was significantly reduced, such that AP-X was only 1.3 times larger. In the resin part of r ≤ 1.5 mm, both resins continued to contract even after light irradiation. The shrinkage strain was almost completed after a period of 3 min.




(a)




(b)

Fig. 2. Average radial shrinkage strain of (a) P90 and (b) AP-X as a function of time during and after LED irradiation.

To calculate the radial normal stress ($\sigma_r$) in the resin, the following stress-strain conversion Eq. (1) must be employed.

$$\sigma_r = E_e \cdot (\varepsilon_r - \bar{\varepsilon}_g) \quad (1)$$

Here, $E_e$ is the equivalent elastic modulus of each resin, and $\bar{\varepsilon}_g$ is the average normal strain at the starting gel point [3]. Table 2 shows the maximum value of the principal strain measured by DIC, the maximum principal stress calculated by Eq. (1) and the maximum principal stress calculated by FEM. For both P90 and AP-X, the maximum principal stress of the interfacial resin measured by DIC is significantly larger than the maximum principal stress calculated by FEM: ~1.6 to 8.3 times for P90 and ~1.5 to 8.4 times for AP-X. Further, the maximum principal stress is approximately 3.6 to 19.2 times higher for P90 and 4.2 to 22.6 times larger for AP-X than the value of contraction stress on the inner surface of the substrate ring [3], calculated from the spring-back force of the substrate. Those large values of σ1 at the margin measured through DIC are considered to be caused by the different radial shrinkage behaviors strongly depending on the r distance from the center, as well as non-symmetric and biased shrinkage distribution in the resin part.

Table 2. Maximum principal strain and maximum principal stress measured through DIC, and the corresponding maximum principal stress through FEM along the resin margin near its interface with PMMA ring

| composite | Principal strain ($\varepsilon_1$)-$\bar{\varepsilon}_g$ (%, Eq. (1)) (SD) | Max. principal stress through DIC (SD) (MPa) | Max principal stress through FEM (MPa) | Contraction stress[3] (SD) (MPa) |
|---|---|---|---|---|
| Filtek P90 | 2.0–10.5 (1.47) | 3.06–16.1 (2.25) | 1.94 | 0.84 (0.12) |
| Clearfil AP-X | 4.0–21.6 (3.24) | 7.44–40.2 (6.03) | 4.80 | 1.78 (0.28) |

## 4. Conclusions

In this study, the local shrinkage characteristics of the composite resin during dental restoration were investigated from the start of light irradiation to the end of the curing test.

As a result of our DIC analysis, the average radial shrinkage strain ($\bar{\varepsilon}_r$) of the resin in the central region was approximately 3.9 times greater for P90 and 2.1 times greater for AP-X than the marginal region of the resin. After the curing test, the maximum $\bar{\varepsilon}_r$ appeared around the center: For both P90 and AP-X, the maximum principal stress measured through DIC was concentrated in the vicinity of the interface: ~3.06 to 16.1 MPa for P90 and ~7.44 to 40.2 MPa for AP-X. These values were ~1.5 to 8.4 times higher than the corresponding maximum principal stress calculated through FEM.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