Relationship between Temperature and Stress of Ultraviolet-Curable Resin during Curing

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Abstract. The temperature and stress of ultraviolet (UV)-curable resin during curing were measured using a system for simultaneously measuring stress and temperature, and their relationship was investigated. The specimen consisted of a mold and UV-curable resin in liquid form. The mold consisted of glass plates, acryl plates and a potassium bromide (HBr) plate. The specimen was irradiated with UV rays downwards from above the specimen. The temperature and stress were measured using thermographic and photoelastic techniques, respectively. The results indicated that the temperature and stress during curing were closely related.

Introduction

High-precision microoptical elements, such as microlenses and diffractive optical elements, made of ultraviolet (UV)-curable resin have been widely used as components in optical systems. However, these optical elements still lack reliability in terms of their mechanical strength. This is because stress tends to become concentrated owing to the shrinkage of the resin, and local deformation and cracks tend to develop easily. The shrinkage occurs as a result of the chemical reaction in the UV-curable resin.

To improve the reliability, it is important to clarify the relationship between the chemical reaction and the stress generated in UV-curable resin during its curing. The degree of the chemical reaction can be estimated by the magnitude of heat, which can be measured as temperature. The stress may be analyzed by a photoelastic technique. The authors previously investigated the relationship between the stress and temperature of UV-curable resin during curing using photoelastic and thermographic techniques [1]. It was found that the stress generated at parts of the UV-curable resin with a high temperature was higher than that at parts with a low temperature.

In this study, we measured the temperature and stress of UV-curable resin during curing using photoelastic and thermographic techniques, respectively, and investigated their relationship in more detail.

Experimental Procedure

Figure 1 shows details of the specimens, which consist of a mold and UV-curable liquid resin. Pentaerythritol triacrylate was used as the monomer in the resin. The mold consists of glass plates, acrylic plates, a potassium bromide (KBr) plate and black vinyl tape. The liquid resin was poured into a cavity surrounded by glass, acrylic and KBr plates. The vinyl tape placed on the left and right sides prevented UV rays from illuminating the left and right sides of the resin, respectively. Figure 2 schematically shows the system used for simultaneously measuring the temperature and stress of the UV-curable resin during curing. The system consists of an infrared camera for measuring the temperature, a photoelastic apparatus (dark-field circular polariscope) for measuring the stress, a beam splitter, which can reflect infrared light and transmit visible light, and a UV irradiation device.

The specimens were placed on a stage so that the KBr plate was oriented in the direction of the beam splitter and irradiated from above with UV rays with a light intensity, E, of 10.0 mW/cm^2 at the top surface of the resin for t=420 s. In this study, isochromatic fringes, which correspond to the difference between the two principal stresses, are referred to as the stress.

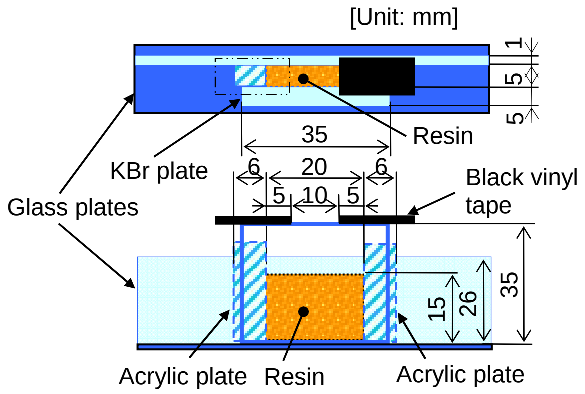

Fig. 1 Shape and dimensions of specimen

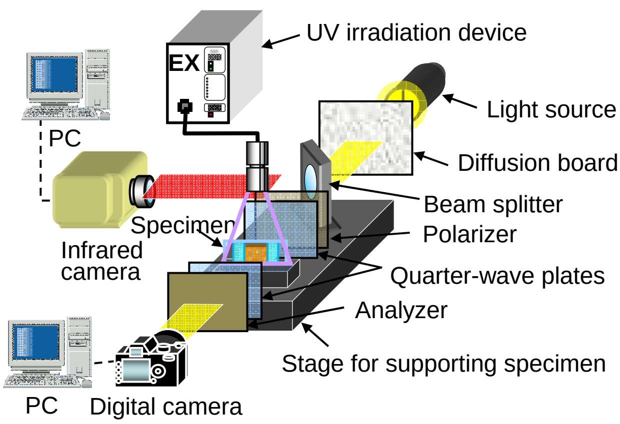

Fig. 2 Experimental setup

Experimental Results and Discussion

Figure 3 shows temperature and isochromatic fringe (stress) images of the resin for UV irradiation durations of *t*=10, 30, 60, 120 and 300 s. In Fig. 3, points 1, 2, 3 and 4, at which the temperature and isochromatic fringe order of the resin were measured, are shown. Figures 4 and 5 show the variations of the temperature and isochromatic fringe order with curing time, respectively. In Fig. 5, the maximum fringe order generated in the resin at each curing time is also included.

Figures 3(a) and 4 revealed that the initial high temperature in the upper area of the resin dissipated in the downward direction. The high temperature is caused by the chemical reaction that leads to curing. This implies that curing started from the upper area of the resin and proceeded downward. In addition, the resin undergoing curing has a high temperature that is retained for a certain time after curing, and the resin that is not yet being cured has a low temperature. Figures 3(b) and 5 indicate that isochromatic fringes (stress) were generated in the upper area of the resin on which UV rays were irradiated. As the curing progressed, the fringes became convex in the downward direction and propagated downward. The order of the isochromatic fringes in the cured area of the resin increased as the curing progressed. The increase in the isochromatic fringe order in the upper part of the cured area was greater than that in the lower part. At *t*=300 s, at which curing was approximately finished, the isochromatic fringe orders in the upper and lower parts of the resin were about 0.75 and zero, respectively. The isochromatic fringe order in the upper area of the resin increased immediately after the temperature in this area reached a maximum, and then the rate of increase decreased with curing time. In addition, the isochromatic fringe order tended to converge to a specific value. These results indicate that the temperature can be useful for determining the state of curing of a resin and how stress is generated in the resin.

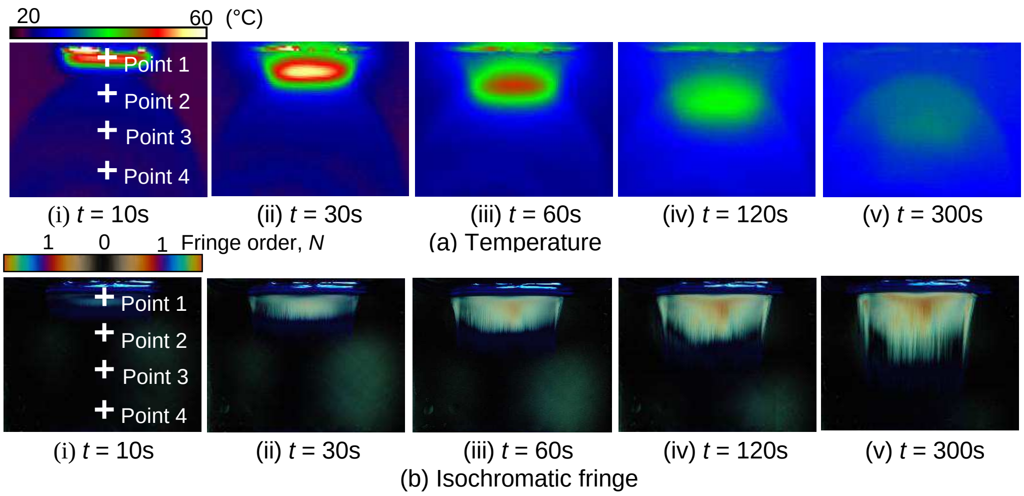

Fig. 3 Time variations of temperature and isochromatic fringe

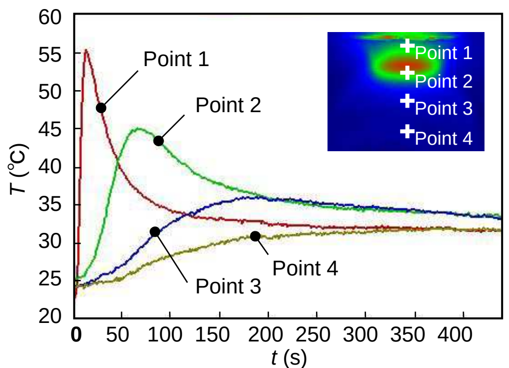

Fig. 4 Time variations of temperature, *T*, at points 1 to 4 shown in Fig. 3

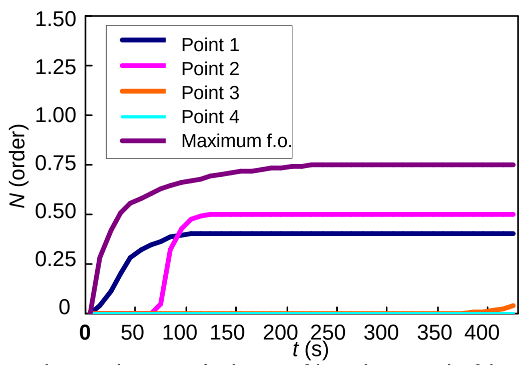

Fig. 5 Time variations of isochromatic fringe order, N, at points 1 to 4 shown in Fig. 3

Conclusions

(1) A high temperature, which was caused by a chemical reaction, appeared locally in the upper area of the UV-curable resin immediately after UV illumination started, and shifted downward.

(2) The isochromatic fringe order (stress) in the upper area of the resin increased immediately after the temperature in this area reached a maximum, and then the rate of increase decreased with curing time. In addition, the isochromatic fringe order tended to converge to a specific value.

References

[1] E. Umezaki and M. Abe: *Development of System for Simultaneous Measurement of Stress and Temperature*, Key Eng. Mat., Vol. 326-328 (2006), p. 163-166.