Optical Fiber Sensor for Monitoring Flow and Resin Curing in Composites Manufacturing

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SUMMARY: An optical fiber has been used as an intensity-based sensor for the monitoring of the fluid front infiltrating a reinforcing fiber mat in composites manufacturing. The sensor length comprised the fiber core, initially surrounded by air or vacuum and subsequently covered by the infiltrating fluid. Two configurations were tested where a step-change or a continual output signal was obtained, respectively. In the latter case, the sensor used in this study demonstrates an improvement of up to two orders of magnitude over conventional monitoring techniques used for this application. This performance is coupled with more obvious advantages of low cost, compatibility with composite fabrication, and ease of use. The sensor was also used to monitor the curing of resin, where the power output was falling as the surrounding resin was curing. The sensor was successful at determining the gel point which was in agreement with rheological data.

KEYWORDS: Optical fiber, sensor, flow, curing, composites.

INTRODUCTION

Infiltration of fiber mats by polymeric liquids in composites manufacturing is generally described by Darcy's law as flow through a porous medium. In one or two-dimensional in-plane flows, flow monitoring is required in the measurement of the in-plane permeability of fiber mats and for purposes of process monitoring and control during manufacturing. Flow/curing sensors positioned at the mold surface include pressure transducers, thermistors and dielectric sensors and may be used in the case of non-transparent molds when the flow cannot be monitored visually. In cases of inhomogeneous permeability and thick laminates, flow sensors are needed between fiber layers to monitor flow variations across the thickness of the fiber mat and flow racing effects where the fluid may race along certain macro-channels between certain fiber layers. SMARTweave [1] is an example of such a sensor comprising a grid of carbon filaments on two non-intersecting planes; it functions on the basis of change in electric conductivity as the infiltrating liquid fills the gap between two crossing carbon filaments. However, its applicability is sometimes limited if it is used within carbon fiber mats due to similarities in electric conductivity between the carbon filament sensor grid and the carbon fiber mat.

Hence, this study focuses on the idea to develop an optical fiber-based sensor system. Optical fibers have been used successfully as cure sensors [2,3] in polymers by relying on changes in the refractive index of the polymer resin as it cures. Fluorescence-based optical fiber sensors have been further investigated for flow monitoring of a polymer resin containing a fluorescent dye [4], where the fluorescence intensity measured by the sensor increased linearly with the sensor length covered by the advancing resin.

PRINCIPLE OF OPERATION

The suggested principle of operation is based on the propagation of light along an optical fiber by total internal reflection if the angle of incidence of a light beam is greater than a critical angle, θ_c, determined from Snell's law

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) \tag{1}$$

where n_1 and n_2 are the refractive indices of the fiber core and its surrounding medium, respectively. Commercial optical fibers consist of a central core surrounded by a layer of cladding of refractive index n_2, where $n_1 > n_2$. An outer plastic coating provides mechanical protection. The losses in the light transmission through such a fiber are proportional to the fourth power of the frequency of the transmitted light, hence the use of low frequency light is preferred: in this study, red light was used as the lowest frequency region of the visible light. Snell's law results in a cone of acceptance of the transmitted light by the optical fiber the angle of which is defined by the numerical aperture, NA, calculated by the relation:

$$NA = \sqrt{n_1^2 - n_2^2} \tag{2}$$

Hence, the greater is NA the lower are the light losses. The number of propagating modes, M, supported by the optical fiber is then given by the equation

$$M = 2\pi^2\alpha^2(NA)^2/\lambda^2 \tag{3}$$

where α is the radius of the fiber core and λ is the wavelength of light. In this project, the length of the optical fiber prepared to act as a flow sensor consisted only of the core, so that the surrounding medium, air, vacuum or process fluid, would act as cladding.

The core of the sensing length of the optical fiber will be initially surrounded by vacuum or air of a refractive index $n_2 = 1$. It will be subsequently covered by the propagating process fluid which will be generally of higher refractive index than air, namely: $n_{2,\text{ epoxy}}$ in the range of 1.44(uncured) to 1.58(cured); $n_{2,\text{ polyester}}$ in the range of 1.53(uncured) to 1.57(cured); $n_{2,\text{ silicone oil}} = 1.402$(often used in permeability measurements). These may be compared with the refractive index of materials used as cladding in commercial optical fibers, for example acrylic where $n_2 =$ 1.37 to 1.49.

Prospective core materials for the optical fiber include silica with n_l = 1.45 to 1.46, lead oxide doped glass with n_l = 1.62, poly(methyl methacrylate) with n_l = 1.49, cured epoxy with n_l = 1.57 and polystyrene with n_l = 1.6. The loss of the optical fiber will vary as the core is increasingly covered by the liquid due to the fact that increasingly fewer modes of light will be able to propagate. The loss will increase with increasing coverage, but will also be a function of both the refractive index and loss coefficient of the liquid. Hence, a particular propagating process fluid has to be matched with the appropriate optical fiber core material.

EXPERIMENTS AND RESULTS

A specially manufactured optical fiber was supplied by Fibercore Ltd consisting of silica core of 125 μm diameter and an acrylic coating of 250 μm external diameter. A laser source of 650 nm wavelength and less than 1 mW power was coupled into one end of the fiber, whilst the output end was connected to a "Fotec" optic power meter to measure the power of the light output. An output of 130 μW was measured in this manner using the optical fiber without any liquid present.

Alternatively, a mid-zone of the optical fiber was stripped of its acrylic coating (air-clad sensor length) and the optical fiber was embedded between glass fiber, reinforcing fabric layers to monitor the flow progress of an uncured epoxy resin in resin infusion under flexible tool (RIFT) (see Fig. 1).

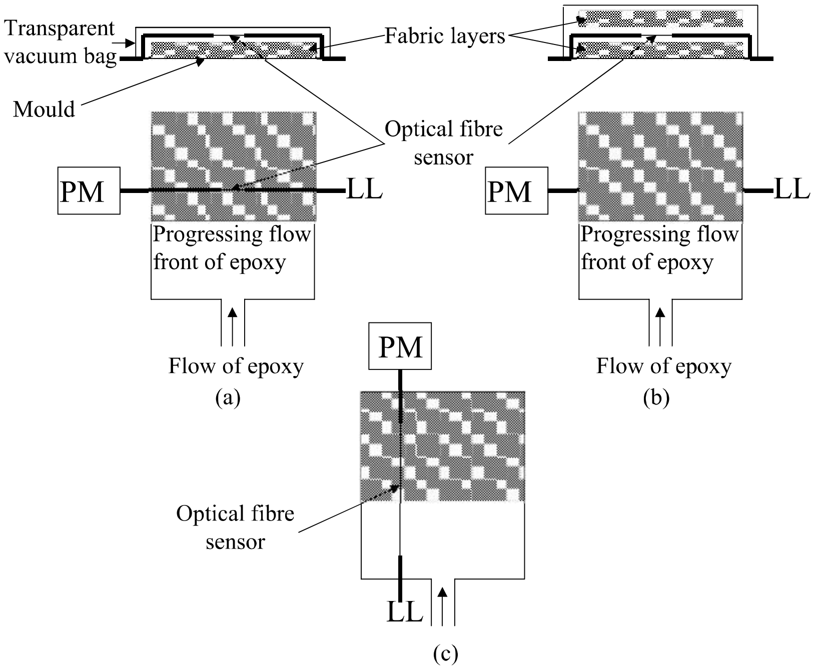


Fig.1. Monitoring the flow front in RIFT where the optical fiber sensor is placed normal (a) and (b) or parallel (c) to the flow direction. LL: laser light; PM: power meter.

In the experiment in Fig.1(a), as soon as the epoxy fluid reached the sensing length the output detected by the power meter fell to about 20% of the value measured when the sensing length was air-clad. Given that the fluid progress at the top fabric layer was monitored visually and with a camera, it was concluded that the step-change in the power meter signal gave an excellent indication of the time at which the flow front covered the fiber. In the experiment in Fig.1(b) where the optical fiber was placed between fabric layers, the signal of step-change in the output measured by the optical power meter was received before the flow was observed to reach the same marked position in the top layer. This clearly indicates flow racing in the middle-layer region which, in turn, demonstrates the effectiveness of this simple sensor in this aspect of composites manufacturing.

In the experiment in Fig.1(c), a 100 mm air-clad sensor zone was prepared and the optical fiber was placed parallel to the flow direction on the top glass fabric layer. The sensor was then covered gradually by the flowing epoxy while the light output was measured by the power meter and the length of fiber sensor covered by epoxy was monitored using a camera. Fig.2 presents the results in which the detected power output falls as the epoxy propagates along the sensor. The reason for this is that the refractive index of the uncured epoxy, n_2, is very close to n_1 of the silica core leading to more weakly confined modes. As the length of the fiber sensor is surrounded partly by air and partly by epoxy, there is a correlation between the optical loss and the extent of coverage by epoxy, as expected. Fig.2 has been constructed by normalising the power output $P_{ep,x}$, obtained when a length x of the sensor is covered by epoxy, to the power output $P_{ep,0}$, obtained when the whole length of the sensor zone was air-clad. The obtained experimental data has been fitted to the exponential loss equation

$$\frac{P_{ep,x}}{P_{ep,0}} = e^{-\alpha x} \tag{4}$$

This results in a loss coefficient α=0.766 cm^{-1}, or expressed in dBs, a loss of 3.3 dB/cm. Taking a typical sensitivity of an optical power meter to be of the order of 1 μW, and the resolution to be 1 μW, then for a typical $P_{ep,0}$ of 130 μW in this study we are able to resolve optical fiber coverage by liquid of up to 6.4 cm, with a resolution of 490 μm. Obviously increasing the optical power will increase the total length that can be measured, and better resolution can be obtained by using an optical power meter with improved resolution. For example, if we increase $P_{ep,0}$ to 1 mW, the fiber coverage increases to 9.1 cm, with a resolution of 65 μm.

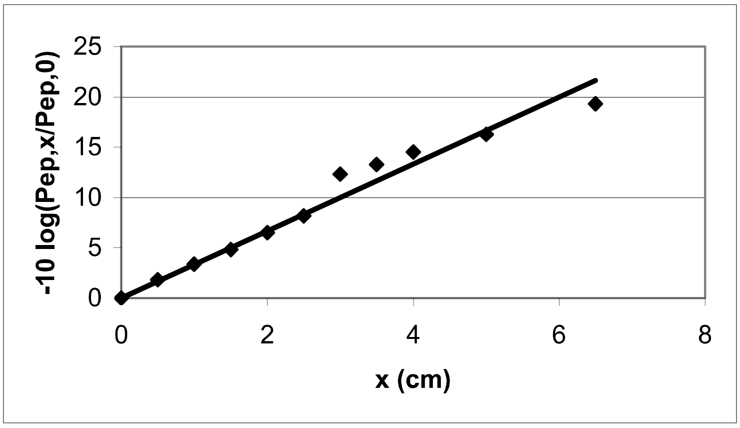
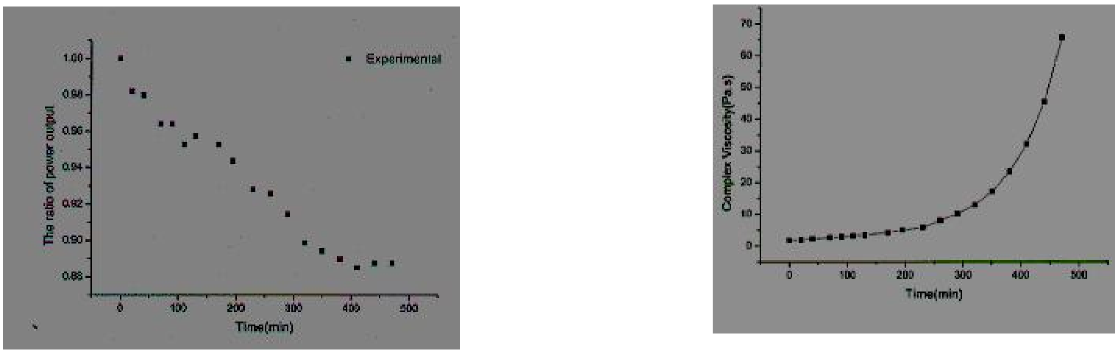


Fig.2. Continual output power signal obtained when a 100 mm flow-sensor zone was placed in the flow direction: experimental data and logarithmic fit according to equation (4).

The last experiment involved the monitoring of curing of the Araldite epoxy system using an optical fiber with a core of n_1=1.65, made by Oxford Electronics Ltd. The result is presented in Fig.3(a) in which the power output decreased as the refractive index of epoxy increased during curing. The output stabilised at about 400 min which agrees with the gel point observed in the viscosity rise in a corresponding rheology experiment in Rheometrics, Fig.3(b)



(a) (b)

Fig.3. Curing of epoxy: (a) normalised power output from the optical fiber sensor; (b) viscosity data from Rheometrics.

CONCLUSIONS

We have demonstrated that a simple, intensity-based optical fiber sensor can be used for the monitoring of flow and curing in composites manufacturing, placed either at the surface of the molding or between fiber layers. The sensor has good resolution and accuracy and is particularly suited to detect flow racing effects or dry spots in critical regions.

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