OPTICAL FIBRE SENSOR FOR MONITORING FLOW AND RESIN CURING IN COMPOSITES MANUFACTURING

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ABSTRACT

An optical fibre has been used as an intensity-based sensor for the monitoring of the progress of fluid front infiltrating a reinforcing fibre mat and the curing of an epoxy resin in composites manufacturing. The sensor length comprised the fibre core, initially surrounded by air or vacuum and subsequently covered by the infiltrating fluid. Two configurations were tested for flow sensing, 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. 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.

1. INTRODUCTION

Infiltration of fibre mats by polymeric liquids in composites manufacturing is generally described by Darcy's law as flow through a porous medium [1]. In one or two-dimensional in-plane flows, flow monitoring is required in the measurement of the in-plane permeability of fibre mats [2] and for purposes of process monitoring and control during manufacturing [3]. Flow sensors are devices that "sense" the flow front as it passes through their location. Flow/curing sensors positioned at the mould surface include pressure transducers, thermistors and dielectric sensors and may be used in the case of non-transparent moulds when the flow cannot be monitored visually. In cases of inhomogeneous permeability and thick laminates, flow sensors are needed between fibre layers to monitor flow variations across the thickness of the fibre mat and flow racing effects where the fluid may race along certain macro-channels between certain fibre layers. SMARTweave [4] 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 fibre mats due to similarities in electric conductivity between the carbon filament sensor grid and the carbon fibre mat.

Hence, this study focuses on the idea to develop an optical fibre-based sensor system. Optical fibres have been used successfully as cure sensors [5,6] in polymers by relying on changes in the refractive index of the polymer resin as it cures. Fluorescence-based optical fibre sensors have been further investigated for flow monitoring of a polymer resin containing a fluorescent dye [7], where the fluorescence intensity measured by the sensor increased linearly with the sensor length covered by the advancing resin.

2. PRINCIPLES OF OPERATION

The suggested principle of operation is based on the propagation of light along an optical fibre 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_l and n_2 are the refractive indices of the fibre core and its surrounding medium, respectively. Commercial optical fibres consist of a central core surrounded by a layer of cladding of refractive index n_2, where $n_l > n_2$. An outer plastic coating provides mechanical protection. The losses in the light transmission through such a fibre 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 fibre 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 fibre is then given by the equation

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

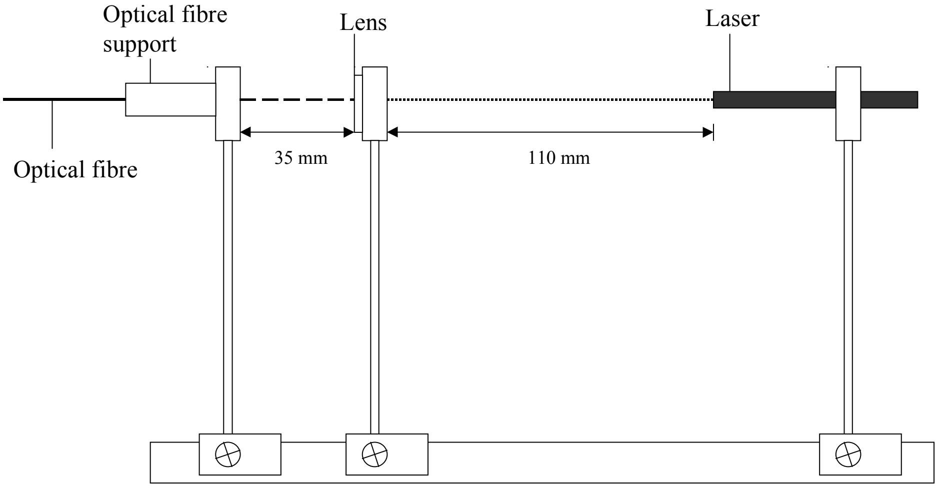
where α is the radius of the fibre core and λ is the wavelength of light. In this project, the length of the optical fibre prepared to act as a flow sensor consisted only of the core, so that the surrounding medium, air, vacuum or process fluid, would act as cladding.

The core of the sensing length of the optical fibre will be initially surrounded by vacuum or air of a refractive index $n_2 = 1$ [8]. It will be subsequently covered by the propagating process fluid which will be generally of higher refractive index than air, namely: $n_{2,\ epoxy}$ in the range of 1.44(uncured) to 1.58(cured); $n_{2,\ polyester}$ in the range of 1.53(uncured) to 1.57(cured); $n_{2,\ silicone\ oil} = 1.402$(often used in permeability measurements). These may be compared with the refractive index of materials [8] used as cladding in commercial optical fibres, for example acrylic where $n_2 = 1.37$ to 1.49. Prospective core materials [8] for the optical fibre 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 fibre 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 fibre core material.

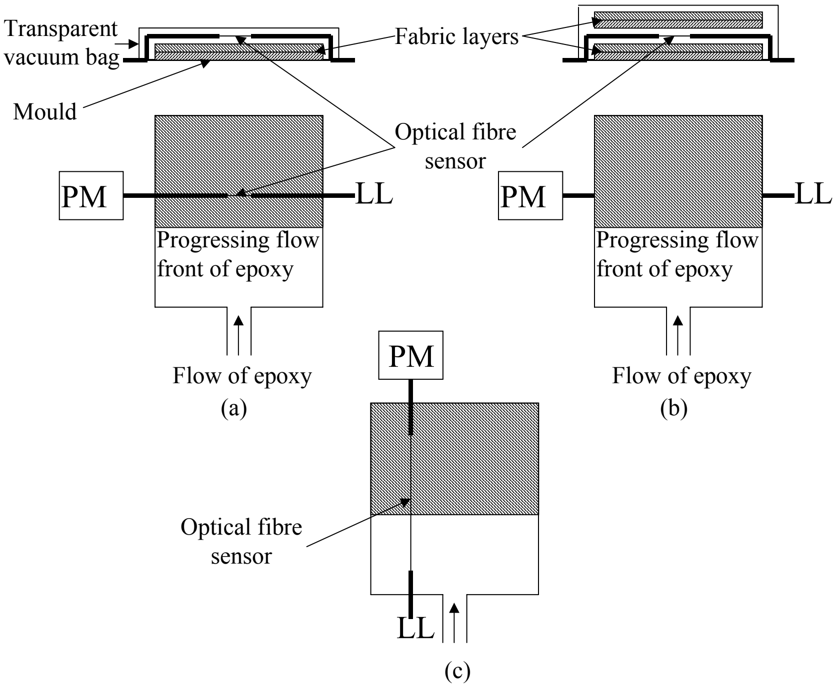
3. MONITORING OF RESIN FLOW

Experimental set-up: A specially manufactured optical fibre 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 fibre (see Fig.1), 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 fibre without any liquid present.

Alternatively, a mid-zone of the optical fibre was stripped of its acrylic coating (air-clad sensor length) and the optical fibre was embedded between glass fibre, reinforcing fabric layers to monitor the flow progress of an uncured epoxy resin in resin infusion under flexible tool (RIFT), a type of composites manufacturing technique (see Fig.2).

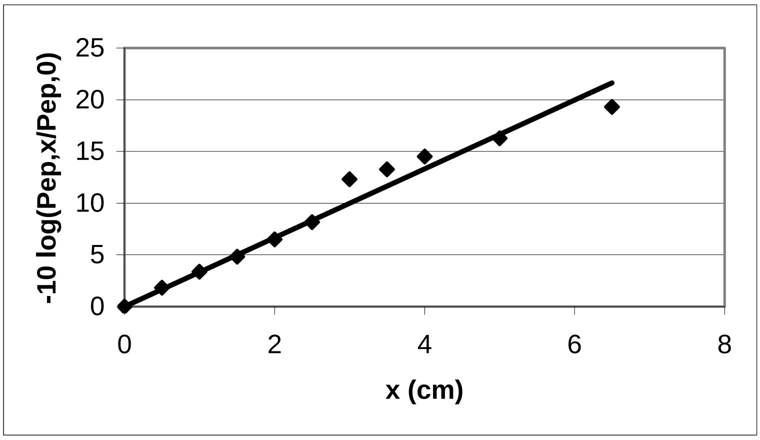


“**Fig. 1.** Experimental set-up including light source and optical fibre.”



“**Fig.2**. Monitoring the flow front in RIFT where the optical fibre sensor is placed perpendicular (a) and (b) or parallel (c) to the flow direction. LL: laser light; PM: power meter.”

Results and discussion: In experiment A, the optical fibre with the air-clad sensor zone was placed perpendicular to the flow direction on the top surface of an assembly of glass fabric layers (see Fig.2(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 fibre. Experiment B was set to investigate the usefulness of the optical fibre sensor to detect flow racing in middle-layer regions. When it was placed between fabric layers (see Fig.2(b)), 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.



"**Fig.3.** 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 (1)."

In experiment C, a 100 mm air-clad sensor zone was prepared and the optical fibre was placed parallel to the flow direction on the top glass fabric layer (see Fig.2(c)). The sensor was then covered gradually by the flowing epoxy while the light output was measured by the power meter and the length of fibre sensor covered by epoxy was monitored using a camera. Fig.3 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 fibre 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.3 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

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

This results in a loss coefficient $\alpha=0.766\ cm^{-1}$, 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 fibre 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 fibre coverage increases to 9.1 cm, with a resolution of 65 μm.

These experiments also indicate that the optical fibre sensor may be used both as a digital or analogue flow-sensor, depending whether it is placed perpendicular or parallel to the flow, respectively (as in Fig.2(a) and (b) against Fig.2(c)). This offers the potential for a number of optical fibre configurations for the monitoring of flow and curing [5], and process control in composites manufacturing. The optical fibre sensors may be used at the surface or between fibre layers in the moulding in contrast to other types of sensors which are used as surface sensors only.

Optical fibres are much thinner (of the order of 100 μm or less) than the gap in SMARTweaves [4], which is generally of the order of 1 mm for electric conductivity sensors. Hence, optical fibre sensors are more sensitive and less intrusive to the properties of the moulding. Alternatively, it is possible to assemble a dielectric sensor [9] with a small sensor gap on a polyimide film, but then this is also a surface sensor and it cannot be placed within the moulding.

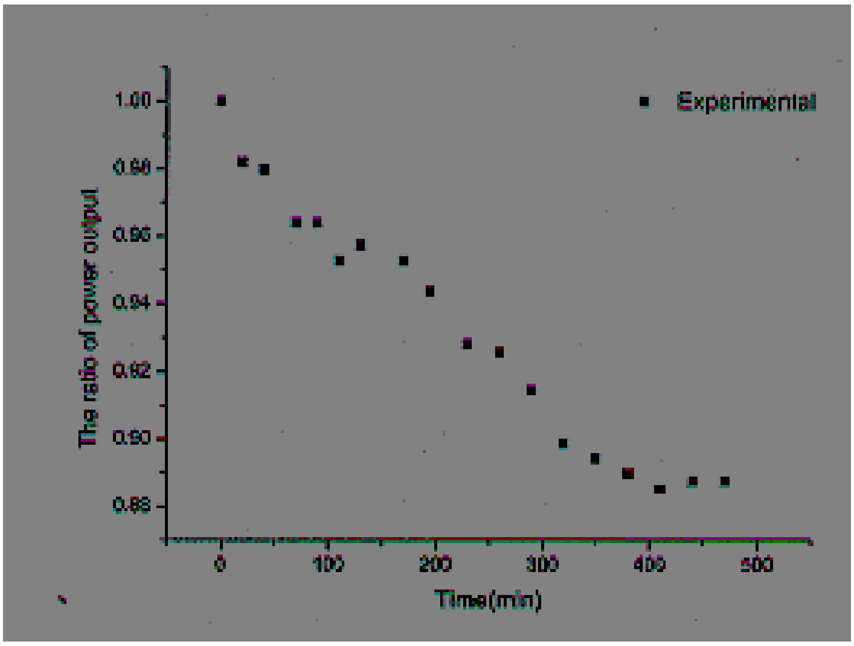
Visual monitoring of the flow front has a resolution of the order of 1 mm for surface measurements, and up to more than 10 mm when the surface measurements are assumed to be equivalent through-thickness average values in the case of fibre multi-layers of different in-plane permeability or when flow racing effects are present. This demonstrates immediately the effectiveness of the optical fibre sensor for the accurate measurement of permeability and process monitoring through the moulding thickness, offering an improvement of up to two orders of magnitude. When compared to the fluorescence-based optical fibre sensor suggested by Kueh et al [7], the latter requires a fluorescent material and a more expensive spectrometer, and it includes an uncertainty of ±10% As a result, the optical fibre sensor proposed in the current study is a low cost, high resolution, high accuracy flow sensor in the measurement of permeability and composites manufacturing, and can also be applied for subsequent cure monitoring.

4. MONITORING OF RESIN CURING

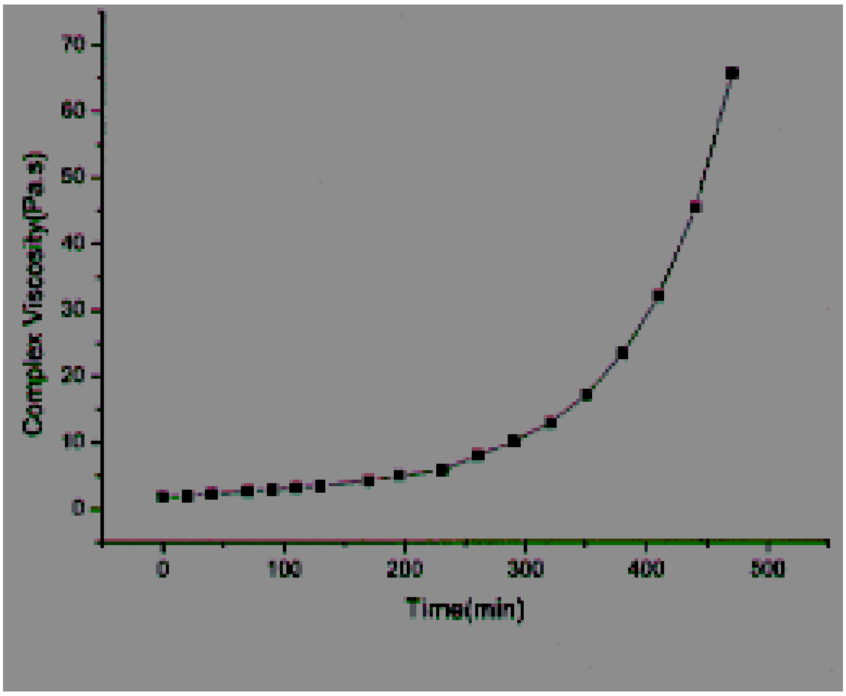
The last experiment involved the monitoring of curing of the Araldite epoxy system using an optical fibre with a core of n_1=1.65, made by Oxford Electronics Ltd. The result is presented in Fig.4(a) in which the power output decreased as the refractive index of epoxy increased during curing. The output stabilised at about 400 min which agrees with the gel point observed in the viscosity rise in a corresponding rheology experiment in Rheometrics, Fig.4(b).

5. CONCLUSIONS

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



(a)



(b)

“**Fig.4.** Curing of epoxy: (a) normalised power output from the optical fibre sensor; (b) viscosity data from Rheometrics.”

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