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Modelling heat transfer through an FBG optical fibre

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ABSTRACT

This paper presents a new approach to model heat transfer through an optical fibre. Three thermal strain modelling procedures were evaluated for coated and uncoated FBG optical fibres, considering different layers of sensors that effect strain measurements. The compensation factors required for strain measurements were investigated. The acrylate coating was found unsuitable for thermosetting polymers due to low *Tg* whereas, polyimide coating was appropriate for cure monitoring due to high *Tg* than most thermoset resins. Three types of thermal strain models were simulated, and the results were compared with experiments. The heat transfer through the core of an optical fibre was found negligible relative to glass cladding and the coating layers. It was found that thermal strains induced by the glass cladding and protective layers become more dominant as the heating rate and temperature range increases. The uncoated FBGs were found to give better accuracy for high temperature applications.

1. Introduction

In recent years, fibre reinforced polymer composites have been used extensively to manufacture large-scale complex components in industries such as aerospace, automotive, and wind energy, stretching the upper limits of these materials. However, at the same time, manufacturers are required to continually ensure high quality components with increased production rate therefore, leading to a more stringent need for quality control of these materials during the manufacturing process. Fibre Bragg Grating (FBG) sensors are widely used for structural health monitoring of composite structures in civil, aerospace, and wind energy industrials [1–7]. Existing strain monitoring equipment such as, Rosette strain gauges provide limited accuracy due to their relative size to the reinforcement fibres [8]. The FBG sensors offer a solution that does not cause disruption to the laminated structure (typically 125–300 μm diameter), are chemically inert, and sensitive to both temperature and mechanical strain. Recently, there has been an increasing interest in using FBG technology for cure monitoring of thermosetting resins for aerospace and wind energy applications [9–11].

Although, much work has been done to characterise FBG sensors for structural health monitoring applications, only a few researchers have successfully reported using FBG sensors in high temperature, low strain, and resin cure or gelation point/time applications. There are numerous offline cure monitoring techniques, but only a few online methods are available [12–21]. This is due to the difficulty in developing cost effective sensors that are small enough to embed without affecting the structural integrity of the component being monitored. Recently new types of cure monitoring techniques are introduced using piezo-electric, piezo-resistive, carbon nanotubes, and graphene coated patches for cure and structural health monitoring. Chilles et al. [22] introduced inductively coupled piezoelectric sensors which were embedded into the composite structure to monitor curing and subsequently damage detection after cure. The system measured the velocity and amplitude of ultrasonic waves received from the laminate. Ghodhbani et al. [23] related the ultrasonic characteristics of curing laminate with full cure kinetics of the resin. Moghaddam et al. [24] used microscale integrated capacitive sensors for real-time cure monitoring. Due to their miniature nature, there were minimum effects found in the mechanical properties degradation. Torres et al. [25] used Tunnelling Junction sensors, which were specifically manufactured using the low pressure chemical vapour deposition method. The use of nanoparticles for cure and structural health monitoring is also gaining attention e.g. Lu et al. [26] used CNT based bucky paper, Moriche et al. [6] used GNPs for strain monitoring, and Ali et al. [27] used a novel graphene oxide coating technique directly on the reinforcements for full process and cure monitoring. Most of these works are proof-of-concept studies which require further in-depth analysis.

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The FBG sensor is a periodic modulation in the core of an optical fibre. The centre wavelength of the light reflected from a Bragg grating is dependent on the refractive index of the core and the periodicity of the Bragg grating. The inner most layer is called the fibre core, this layer allows light of different wavelengths to travel through the fibre. The fibre core is surrounded by a cladding layer, which is made from silica glass. The glass cladding layer usually has identical properties to the core except for a slightly lower reflective index. This difference in reflective index results in total internal reflection occurring between the two layers, preventing light from escaping the core. The outer most layer is called the protective coating. This layer protects the glass fibre layers from moisture and physical damage. The FBG sensors are sensitive to temperature change, which affects both the refractive index and the periodicity of the grating. During the curing process of a thermosetting polymer, embedded FBGs are subjected to elevated and fluctuating thermal loads [28–33]. When considering different FBGs for any strain measurements, the question of whether the protective coating has an effect on the strain readings is an important question to answer. As the coatings transfer both the mechanical and thermal loads between the host material and the core of the optical fibre. Much is known about the characteristic behaviour and response of the core of an FBG sensor [34–36], but very little is known about how the protective coating and glass cladding layers effect strain measurements.

The FBG grating has been modelled in many different ways [37–44]. Coa et al. [43] developed a numerical three-dimensional simulation using a finite difference time domain algorithm to simulate the light wave propagating through the core and glass cladding layers of an optical fibre. Her and Tsai [45] investigated how the protective coating and adhesive layers of an FBG (embedded into a host material) effected the strain transfer between the host and optical fibre. A theoretical model was developed, and the results were validated using the finite element method. The theoretical model found good agreement with experimental results. Her and Tsai also conducted a parametric study in which they showed that the higher the elastic modulus (stiffness) of the coating with longer embedded length, the better the strain transferred to the optical fibre. Although, the study incorporated the effects of mechanical strain transfer on a coated optical fibre, but it did not consider how the coatings effected the measured thermal strains.

The authors believe that reported modelling approaches in the literature are not suitable for in-situ cure monitoring, due to the fact that these applications tend not to be subjected to large fluctuations in temperature. It is well documented that the FBG sensors are sensitive to thermal and mechanical strains (as defined by Meltz's equation) [13]. However, this equation only defines the periodic grating within the core of the optical fibre. The core cross sectional area makes up only a small percentage of the total area of an uncoated or coated FBGs (0.5% and 0.1% respectively). Therefore, a large percentage of the optical fibre is not well defined. The majority of commercially available optical fibres are coated therefore, if they are to be used for cure monitoring, it is important to understand how these coatings effect thermal strain measurements. Therefore, in this paper, several numerical methodologies will be discussed in order to help understand and improve cure strain measurements.

The research presented in this paper has high relevance to the advanced composites sector where a robust understanding of heat transfer through an FBG fibre-optic sensors is required. The paper focuses on modelling the temperature distribution at different points within an optical fibre, using three different levels of modelling complexity to determine the corresponding thermal strains at these points. For each of these models, an uncoated, polyimide, and acrylate coated FBGs are considered. The objective of this paper is to present different approaches to model coated and uncoated FBG sensors, in an effort to understand how different layers of an FBG optical fibre effect thermal strain measurements. A heat resistance network is used to model the heat transfer through the whole optical fibre. The models are concerned with the fibre optic alone and not the bulk composite therefore, the heat rate effects are not an operative in this modelling approach. Finally, the modelling results are compared with experimental heating cycle.

Table 1
Different optical fibre types used for FBG testing.

Fibre core® identification (Single mode fibre)		Dimensions		
		Protective coating	Glass cladding	Core
		(μm)	(μm)	(μm)
SM1500	Acrylate	310 ± 5	198 ± 5	9 ± 0.1
	Polyimide	300 ± 5	125 ± 5	9 ± 0.1
	Uncoated	–	198 ± 5	9 ± 0.1

2. Materials and methods

Three commercially available optical fibres FIBRE CORE ® SM 1500 were chosen for this study as shown in Table 1. Before testing, all optical fibres were annealed at 150 °C for 3 h to ensure stable normalised wavelength readings were obtained. Optical microscope and Environmental Scanning Electron Microscope (ESEM) images were used to find out dimensions of each fibre, see Fig. 1. Acrylate or any other polymer can also be removed by combustion at a temperature close to 400 °C, but this procedure may give rise to crack formation on the fibre surface. In many cases, polymer coating can be removed by standard mechanical peeling, but caution must be taken to avoid breaking the fibre. The uncoated fibres were prepared by removing the coatings from the Acrylate fibres by immersing the fibres in dichloromethane for 3 min, then gently sweeping the fibre with a paper towel. The sensors used in each experiment consisted of FBGs with a grating length of 25 mm. The wavelength shift was recorded using an Insensys three channel OEM-1030 and Fibre Sensor Interrogator (FSI) unit, and temperature was recorded using National Instrument (NI) mainframe model SCXI-1000 with an 8-channel SCXI-1112 thermocouple module running Labview software. The glass transition temperature (Tg) of the acrylate and polyimide optical fibre coatings were determined using a TA instruments Differential Scanning Calorimeter (DSC).

2.1. Temperature and strain calibration

To find out the temperature sensitivity factor (TSF) β, the FBG sensors were placed inside a copper tube with a K-type thermocouple as shown in Fig. 2a. This was necessary to reduce small changes in strain due to temperature fluctuations created by the rotation of the oven fan during the experiment. A staggered heating and cooling cycle was designed to ensure thermal equilibrium was achieved, and the corresponding wavelength shifts were recorded. A standard cure schedule was used to observe the response of the FBG's. The temperature was increased at 2 °C/min and after reaching 100 °C, the temperature was held for 100 min (dwell temperature), and then cooled down at 2 °C/min.

To find out the strain sensitivity factor (SSF) K, an apparatus shown in Fig. 2b was used to calibrate the FBG sensors against force. Weights between 25 and 500 g were attached to one end of the optical fibre, and the corresponding wavelength was recorded using an Insensys FSI unit. The applied strain on the optical fibre during this test was calculated as follows;

$$\varepsilon_{applied} = \frac{F_{applied}}{A_{FBG}E_{FBG}} \tag{1}$$

where A_{FBG} is the cross sectional area of the optical fibre and E_{FBG} is young's modulus of the optical fibre.