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A Photonic Crystal Fiber Based Polarimetric Sensor for Cure Monitoring of Magneto-Rheological Smart Composite Material

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A photonic crystal fiber based polarimetric sensor for cure monitoring of magneto-rheological smart composite material

M. Ramakrishnan, G. Rajan, Y. Semenova, Y. Zhou, S. Jerrams and G. Farrell

A buffer stripped high birefringent photonic crystal fiber based polarimetric sensor is developed for monitoring the curing process of magneto rheological elastomer (MRE) smart composite material. Using the developed sensor, different phases of the MRE curing process are clearly visible from the phase shift variation of the embedded polarization maintaining photonic crystal fiber (PM-PCF) sensor. During the curing process the buffer stripped PM-PCF exhibits a stress/ strain induced phase shift variation from 0 to 1.98 radians. This is a significantly large phase change, which can be used to very clearly identify the different stages in the curing process. For comparison, a Fibre Bragg Grating (FBG) sensor is also used for monitoring the internal strain during curing process and its response does not allow one to reliably distinguish all the curing stages. The present investigation offers a simple non destructive method to monitor the curing process of MRE smart composite material.

Introduction: Magnetorheological (MR) materials are a class of smart materials having mechanical properties that can be controlled by an external stimulus [1]. MR materials are solid or liquid materials composed of magnetizable (usually iron) particles suspended in a low permeability carrier matrix (usually rubber). Components made from such controllable MR materials have the distinct advantage that their stiffness, modulus and damping properties can be changed instantly and reversibly by applying an external magnetic field, making them a truly useful "smart material". MR materials have potential applications in a variety of areas from medical to automotive and aerospace for controlled movement/motion in dampers, brakes and vibration absorbers [1]. However in controlled movement applications, it is critical to have accurate control of the MR material properties. One reliable approach to realize this is by using embedded fiber optic sensors.

Compared to conventional non-destructive sensing techniques, optical fiber sensors have achieved wide acceptance due to their attractive properties such as small size, immunity to electromagnetic interference and low cost [2]. Optical fiber sensors embedded in various structures are very useful for applications such as structural health monitoring [2] using Fiber Bragg gratings (FBG) while optical fiber based refractometers [3] have been reported for in – situ characterization of the cure process in composites. Highly birefringent fiber based polarimetric sensors [4] were reported earlier for structural health monitoring applications of fibre reinforced composite materials.

In this letter we present a highly birefringent photonic crystal fiber based polarimetric sensor to monitor the internal stress/strain during the curing process of an MR material, in order to determine the rate of cure and the curing phases. The sensing element is a photonic crystal fiber (PCF) with its buffer coating removed at the sensing area. Removing the buffer coating results in a sensor which exhibits good sensitivity to both non uniform strain and stress variations. To the best of our knowledge the application of such a stripped photonic crystal fiber based polarimetric sensor is the first time an optical fibre sensor has been deployed for cure process monitoring of MR materials.

Experiment: In this work we fabricated a solid MR elastomer (MRE) sample by suspending ferromagnetic soft carbonyl iron particles (diameter ~ 6.0 - 7.0 µm, and density = 7.86 g/cm3 from BASF, Germany) in a low permeability silicone rubber carrier matrix. The silicone rubber carrier matrix is formed by mixing a room temperature vulcanized (RTV) silicone rubber comprising a base elastomer (ESSIL 291 silicone resin) and a catalyst (ESSIL 291 catalyst) in the ratio 10:1. Further, carbonyl iron particles are incorporated into the silicone rubber carrier matrix in a concentration of 20 volume percent. After degassing, the mixture is poured into a mould. Before closing the mould, the optical fiber sensors were placed in the compound as shown in Figure 1(a). The closed mould with compound and optical fiber sensors is allowed to cure in the presence of a magnetic field using a Halbach array, which is capable of providing a mean magnetic flux density of 400 mT (± 5%) over the 50 mm nominal diameters of the bore and is as shown in Figure 1(b). For the present investigation, the orientation of the mould inside the Halbach array is such that during curing process the iron particles align parallel to the direction of optical fiber sensors. The cured sample with optical sensors has dimensions of 5 cm x 5 cm x 0.2 cm and is as shown in Figure 1(c).

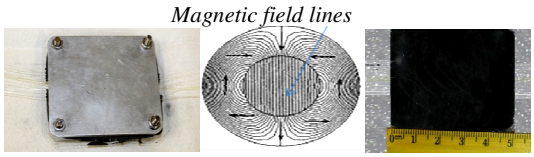

Fig. 1 *(a) Optical fiber sensors placed within mould, (b) Halbach Array, and (c) Cured MRE composite with optical fiber sensors*

The polarimetric sensor used for this study is a buffer coating stripped highly birefringent (HB) PM-PCF polarimetric sensor (PM-1550-01)). The PM-PCF stripped sensing area is located within the 5 cm length of the MRE sample. For comparison, an FBG sensor is used for strain measurement within the MRE sample. It is a polyimide coated FBG having a 1550 nm peak wavelength and the 5 mm grating length placed. The experimental arrangement for monitoring the curing process of the MRE using the polarimetric sensor and FBG sensor is as shown in Figure 2(a). During the entire curing cycle, the mould filled with the MRE mixture with optical fibers is fixed inside a Halbach array. For polarimetric sensors, the variation in State of Polarization (SOP) is measured using a polarization controller and polarimeter (TXP 5004 from Thorlabs). Input light from the laser source (1550 nm) is launched into the polarimetric sensor with its linear polarization at 45^0 to the slow axis of the optical fiber by using a polarization controller. The output fiber from the MRE sample is connected to a polarimeter. During the curing cycle, the information about the phase shift variation of the PM-PCF polarimetric sensor can be determined by evaluating SOP evolution and a more detailed description of this method is provided in reference [5]. For the FBG sensor, the peak wavelength shift is recorded using an FBG interrogation system from Smart Fibers.

Principle: In the case of HB PM optical fibers, any symmetric deformation effect induced by strain influences the propagation constant of every mode propagating through the fiber optic fiber due to changes in fiber length and the refractive indices of both the fiber core and the fiber cladding [6]. This leads to phase shift between the two polarizations of the fundamental mode.

It was reported previously that for a PM-PCF sensor embedded in a composite material the presence of the buffer coating plays an important role in its temperature/strain sensitivity [5]. For stripped PM-PCFs (such as PM-1550-01) the influence of temperature on fiber birefringence in free space is negligible [5]. However, as was reported earlier, the stripped PM-PCF sensor shows an increased temperature induced response after embedding in the composite material [5]. This is due to the fact that the buffer stripped fibre is sensitive to both applied longitudinal strain and composite material thermal expansion induced non -uniform lateral strain / stress. Also, the typical strain sensitivity of a stripped PM-PCF sensor in free space is 1.7 rad/ m. mε. However after embedding in an E-glass fibre reinforced composite material the stripped PM-PCF showed elevated strain sensitivity due to the change in birefringence. For a buffer coating removed PM-PCF polarimetric sensor such an additional variation in birefringence is created both by non - uniform lateral strain components as well as stress induced shape deformations of the optical fiber.

For conventional FBG sensors the Bragg peak wavelength shifts in accordance with the applied longitudinal strain and temperature [2].

Results and discussion: A comparison of responses of the buffer stripped PM-PCF polarimetric sensor and the polyimide FBG sensor during the MRE curing process is carried out. For comparison with the FBG sensor, the real time changes in Bragg peak wavelength are also recorded using the FBG interrogator. Further, the polarimetric sensor's

phase shift variation and the FBG sensor's Bragg peak wavelength shift are plotted against curing time as shown in Figure 2(b).

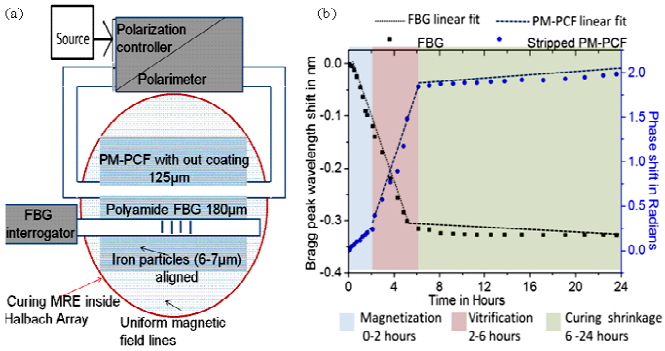

Fig. 2 (a) *Proposed experimental setup for cure monitoring of MRE (b) The MRE sample cure monitoring using PM-PCF and FBG sensors*

Considering Figure 2(b), it can be seen that in the case of the stripped PM-PCF sensor, an overall phase shift of 1.98 radians is observed during the 24 hour MRE curing process. Further inspection of the data in Figure 2(b), shows that the curing process response of the PM - PCF sensor can be divided into three linear response regions with three different slopes. During the 24 hour curing cycle the FBG embedded in the same MRE sample showed blue Bragg wavelength shift from 0 to - 0.32 nm but the overall the FBG response shows only two linear regions are clearly visible as shown in Figure 2(b). The observed Bragg wavelength shift has a blue shift which indicates compressive strain. Considering the typical FBG stain sensitivity as 1.2 pm/ με, and thus the strain variation observed for FBG during curing process is fairly low with a value of - 0.386 mε. In order to differentiate between the separate stages of the curing process based on the PM-PCF sensor response, we have calculated the slopes of the three linear response regions of the PM-PCF sensor response and listed them in Table 1. For comparison, the different slopes of the FBG sensor response are also detailed in Table 1.

Table 1: Rate of change of Phase shift for PM-PCF sensor and rate of change of Bragg peak shift for FBG

Duration	Slope PM-PCF response (Radians/ hour)	Slope of FBG response (nm / hour)
0 - 2 hours	~ 0.11	~ 0.055
2 - 6 hours	~ 0.37	~ 0.050
6 - 24 hours	~ 0.0155	~ 0.00551

The curing phase corresponding to a fluid to solid transition is called vitrification [4] and the associated solvent - matrix chemical reactions occur between the 2nd and the 6th hour of the curing cycle. The stress/ strain exerted at the vitrification stage are expected to be greater than in the initial magnetization stage (from 0 to 2 hours) in which the MRE mixture is not fully solidified and thus the aligned ferromagnetic iron particles within the mould will exert a comparatively low stress / strain on the embedded optical fiber sensors. From Table 1, it is obvious that the slope of the stripped PM-PCF response during the second linear response region (from 2 to 6 hours of curing process) is higher than the first linear response region (from 0 to 2 hours). Finally, the slope of the third linear response region of the stripped PM - PCF sensor is very low as shown in Figure 2(b) and Table 1, indicating a low stress/ strain during this curing stage. During the first two hours the MRE mixture is in the form of a fluid and at this phase the ferromagnetic ion particles are free to align in the direction of the magnetic field - magnetization phase. Vitrification [2] occurs during the 2nd to 6th hours of the curing cycle. In the last phase of the curing cycle from the 6th to 24th hour the chemical process ceases and a slow curing shrinkage takes place due to solvent evaporation. The measurements with stripped PM – PCF sensor confirm that the phase shift variations observed are consequences of the strain and stress during the expected curing phases

Analyzing the response of the FBG sensor, it should be noted that the change in the slope of wavelength shift during the first two phases of curing is insignificant since we expect the slope of second phase higher than first. A clear weakness of the FBG sensor is that the response does not allow one to reliably distinguish between these two curing phases as shown in Figure 2(b). This difference in the curing response of the stripped PM-PCF polarimetric sensor and FBG sensor is due to the fact that for buffer coating removed PM-PCF polarimetric sensors there are two factors contributing towards the output phase variation. The first one is the birefringence variation caused by non - uniform lateral strain components resulted from shrinkage during curing. The second one is the birefringence variation of the PM-PCF sensor caused by the deformation of stripped PM-PCF sensor as a result of the alignment of ferromagnetic iron particles in the direction of the applied magnetic field. However, the Bragg wavelength shift from the FBG sensor does not adequately represent the change in such non-uniform lateral strain components and shape deformations of the optical fiber, and thus the FBG sensor fails to detected different phases of the MRE curing process. It can be concluded that a buffer stripped PM-PCF polarimetric fiber sensor is a suitable candidate for identifying the curing stages by measuring the internal strain /stress components that evolved during MRE curing the process. The FBG measurements showed that the difference between the first two stages of curing process is not as pronounced as in the case of PM-PCF sensor

Conclusion: An embedded stripped PM-PCF sensor is demonstrated for distinguishing different stages of the MRE curing the process. The developed sensor identified the non-uniform strain/ stress components that evolve during different phases of the curing process. From the result we can conclude that more accurate cure monitoring is possible using stripped PM-PCF sensors. Also we believe a buffer stripped PM-PCF can be used for practical applications of MR smart composite material such as characterization of MR properties in presence of a magnetic field. Thus the proposed sensor has a wide range of applications in MR materials at all stages from fabrication to use in areas from medical to automotive and aerospace industries.

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