Monitoring of composite material processing and commissioning using a suite of optical fibre sensors

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A unique characteristic of optical fibre sensors is that they can be embedded within a composite part to monitor the entire manufacturing process because of their small diameter, typically 80-125 µm. They are suitable for embedding into carbon fibre reinforced composites as, unlike the dielectric sensors, they do not have electrical connections. This offers unrivalled capability to monitor composite material processing on-line and *in-situ*. It is important to monitor critical manufacturing stages, so as to guarantee consistent quality in the product. The progress of infusion, the degree of cure, temperature and strain development are important parameters to monitor.

A suite of optical fibre sensors were embedded in various composite parts, both simple and complex shaped. The composite parts included components manufactured from prepregs, hand-laid preforms, and preforms made by the automatic dry fibre placement (ADFP) process using an industrial robot system. The components included aerospace structures such as tail-cones and wings, and industrial superconducting magnets. Some of the preforms were reinforced by through-thickness tufting. Infusion and cure of the laid-up components was carried-out using various processes; resin transfer moulding (RTM), vacuum bagging in an oven, and autoclave systems in both laboratory and industrial environments.

The tufting of the composite preform was monitored using multiplexed fibre Bragg grating (FBG) strain sensors which were affixed to the tufting needle. The infusion of resin through dry fibre composite preform was monitored by detecting the change in refractive index surrounding the optical fibre when the resin arrived at the sensors locations. Optical fibre Fresnel refractometers, tilted fibre Bragg grating (TFBG) sensors, tapered optical fibre sensors, and chirped long period grating (CLPG) sensors were used for infusion monitoring. The subsequent cure of the resin was monitored by measuring changes in the refractive index of the resin using Fresnel refractometers, TFBG sensors, long period grating (LPG) sensors, and also by monitoring the development of transverse strain as a measure of resin gelation using FBG sensors fabricated in highly linearly birefringent (HiBi) fibre. Such strain measurements are also necessary for determining the presence of residual strain, a property that also characterises the quality of the final composite part. A number of HiBi FBG sensor orientations within the preforms were investigated. The HiBi FBG sensors were also used to measure the longitudinal and transverse strain during the subsequent mechanical testing of the final composite part.

The monitoring of the load experienced by the needle during tufting could provide vital information on a number of important issues; wear of the needle, the mechanical configuration and alignment of the tufting head, detection of damage caused to the reinforcing fibres, resin build-up on the needle when tufting prepregs or binders, and the influence of the ADFP process on the composite quality. The experimental results showed that it is also possible to determine the number of layers locally within preform.

A multiple channel fibre optic Fresnel refractometer was developed exploiting electronic-board lock-in amplifiers, allowing measurements to be made at multiple locations within the component simultaneously. The refractometer relies on monitoring the amount of light reflected off a cleaved end of an optical fibre and was used to monitor resin infusion and cure. The arrival of resin at the location of the sensor is detected as a sudden attenuation in the reflected light signal. Infusion, both in-plane and through-thickness, was performed with aerospace resins such as RTM6 into carbon fibre preform laid up by various processes. The measurements demonstrated the capability of the sensors to map the presence of resin at specific locations within the preform and to map the flow of the resin during infusion.

Experimental characterisation of the resins in terms of the degree of cure and change in the refractive index during cure were performed. The degree of cure was determined from temperature-modulated differential scanning Calorimetry (DSC) measurements. The change in the refractive index of the resin was measured using the Fresnel refractometer. The refractive index was well correlated with the degree of cure, providing a correlation function for an isothermally cured resin. Good correlation between the refractive index change and degree of cure was also obtained when resin systems were modified by the addition of multi-walled carbon nanotubes (CNT).

The refractive index of a medium immediately surrounding an optical fibre can be measured using an optical fibre taper, because it facilitates strong interaction between the light propagating in the fibre and its surroundings. High spatial resolution optical frequency domain reflectometry was used to interrogate a serial array of multiplexed tapered optical fibre sensors (50 µm diameter) when monitoring resin infusion. The technique relies on monitoring the change in the attenuation of the Rayleigh backscattered signal from the tapered regions. The tapers were used to monitor resin infusion, both in-plane and through-thickness, in carbon fibre preforms.

The core–cladding mode coupling resonances of TFBG and of LPG sensors are sensitive to the refractive index of the surrounding medium. Multiplexed TFBG sensors of relatively large tilt angle have been used to monitor resin infusion at multiple locations within carbon fibre preform. The coupling to the cladding mode (on the blue side of the Bragg resonance) from a TFBG of relatively low tilt angle is insensitive to the surrounding refractive index and such TFBGs have been used to measure temperature during resin cure. The response of an LPG to the refractive index of the surrounding medium is manifested as a shift in the central wavelength of the attenuation bands. A CLPG was demonstrated for monitoring the direction of flow of resin during infusion. The asymmetry in the CLPG provides the ability to distinguish the direction in which the resin flows over it. Both uniform period LPG and CLPG sensors were used to monitor the cure process of a UV-cured resin and the results compared very well to results from a Fresnel refractometer.

HiBi FBG sensors were embedded in glass fibre/epoxy composites to monitor the effective transverse strain development during cure. The transverse strain demonstrated high sensitivity to the degree of cure and this sensitivity was shown to depend on the orientation of the HiBi FBG sensors to the reinforcement fibres. HiBi FBG sensors were also embedded within superconducting magnet structures. The superconducting magnets were infused with MY750 resin system and cured in an autoclave. The sensors were subsequently used to monitor orthogonal strain components during energisation and quench processes which are part of the commissioning process of the magnets.

In summary a range of optical fibre sensors have been used to measure refractive index and strain during the processing of carbon and glass fibre reinforced composites, from which information on the infusion and degree of cure of the resin, and the development of residual strain can be determined. FBG sensors were also used to monitor the strain on a tufting needle.