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Monitoring high-pressure silicone oil flow using fibre Bragg gratings for fast manufacturing of composite materials

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ABSTRACT

High-pressure resin transfer moulding is a novel process to manufacture composite materials, having the advantages of allowing fast moulding speed and strong part performance. One of the most significant difficulties of the process is that the flow of resin used inside a closed mould cannot be directly monitored. In this paper, a fibre Bragg grating (FBG) sensor is embedded into the glass fibre layers placed inside the mould with the purpose of monitoring the resin flow in the process. This is achieved by heating the mould and measuring how the cold resin flows through the mould using a series of FBG sensors. Results find out that the FBG peak wavelength sharply decreases when the resin reaches the position of the sensor, allowing the monitoring of the flow front through a closed mould. The method is validating comparing FBG measurements with camera recording to visualise the actual position of the fluid. Although FBG sensors respond to both temperature and strain changes, the sharp thermal impact can be easily detected, making unnecessary any temperature-strain discrimination.

Keywords: Fibre Bragg grating, resin flow monitoring, resin transfer moulding, in-situ monitoring

1. INTRODUCTION

Fibre composite materials have the advantages of having light weight, high strength, and strong plasticity. Whilst they are widely used in various fields, the corresponding moulding process of fibre composite materials has also developed rapidly in the last years. The high-pressure resin transfer moulding (HP-RTM) process is a new fibre composite manufacturing process that has recently emerged. The main steps consist of laying glass fibre layers inside a mould, closing the mould and vacuuming, heating the mould, injecting resin at high pressure, applying heat preservation and curing¹. The use of high-pressure injection can make the resin quickly and fully infiltrate the glass fibres, greatly shortening the moulding time of fibre composite materials. A key step in the process is the injection of high-pressure resin, which is highly beneficial to further increase the glass fibre volume fraction and improve product performance. For this process, the mould is required to have extremely high airtightness, and hence, HP-RTM products are usually manufactured by closing the upper and lower dies of the mould. During the process, the flow state inside the mould cannot be measured directly. At the same time, under the influence of factors such as the micro random arrangement of fibre bundles in the composite material and edge effects caused by the difference between fibre cutting and mould size, the flow state inside the mould is very complex and diverse. Obtaining the flow state inside the mould becomes a key factor to optimise the moulding process parameters and improve the quality of the parts. At present, the main resin flow monitoring methods in RTM processes are based on the use of thermocouples², dielectric detection³, and optical fibres⁴. For the HP-RTM process, some reported monitoring methods are based on embedded temperature and pressure sensors inside the mould⁵; however, this has certain limitations, requiring the modification of the mould, and making it impossible to monitor the resin flow inside the glass fibre structure.

In this paper, a method based on fibre Bragg grating (FBG) sensors is proposed and validated to monitor the resin flow in HP-RTM using closed moulds. The method is experimentally validated by comparing the response of a series of FBG sensors placed at different locations inside the mould with images captured by a video camera that shows the actual position of the resin while flowing inside the mould. Result show that although FBG measurements are affected by both temperature and strain changes, the beginning of a sharp thermal change determines the exact time when the resin reaches a given FBG sensor. It is expected the method can be useful to monitoring in real-field closed mould where normally other methods are not properly working or are invasive to the HP-RTM process.

2. PROPOSED FLUID MONITORING BASED ON FBG SENSING

2.1 High pressure moulds and measurement devices

In order to observe the flow of fluid, a mould with transparent upper die is fabricated to simulate a real fully-closed HP-RTM metal mould. As shown in Fig. 1, the mould has a rectangular shape, having a lower metal die that is provided with two symmetrical cavities, which are separated by a raised strip in the middle and meet at one of the ends. Unidirectional glass fibre reinforced plastics (GFRP) are placed in the two cavities. To validate the FBG-based resin flow monitoring method proposed in this work, the upper die of the mould is made of polymethyl methacrylate, this means it is transparent, so that the fluid flow can be observed by a video camera during the injection process. This way, the images captured by the camera at different moments are used to compare the position and timing of the resin flow front with the measured response of each FBG sensor.

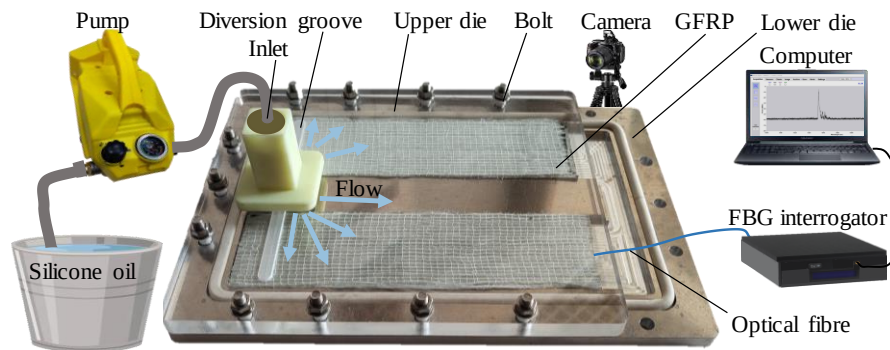


Figure 1. Schematic diagram of HP-RTM experimental setup used in this study.

The upper and lower moulds are locked by bolts and nuts to obtain high pressure to compress the multi-layer GFRP pre-placed in two mould cavities with embedded optical fibres. To facilitate the connection of the FBG sensors to an external interrogator, the upper die of the mould is shorter than the lower die, allowing the optical fibre to exit the mould. An injection gun is aligned with the inlet of the upper die, and the high-pressure liquid is injected into the diversion groove of the upper die. Due to the direct contact between the splitter and the GFRP material, the high-pressure liquid enters the mould and quickly penetrates into the GFRP layer of the two cavities and diffuses along the direction of the glass fibre. This way, the process avoids the glass fibre wrinkle of GFRP caused by the excessive impact force of high-pressure fluid during the injection process, which affects the quality of actual parts.

2.2 Sample preparation and experiment

The material used in the experiment is multilayer unidirectional GFRP superimposed and pressed. First, according to the size of the mould, twelve 250mm × 70mm GFRP pieces are prepared. Six of these are placed in each of the mould cavities of the lower die, as shown in Fig. 2(a). An optical fibre with six FBG sensors is placed between the 1st and 2nd top plies of the GFRP stack, as shown in Fig. 2 (b), while one of the fibre ends is left available to access the FBG interrogator placed outside. The FBG sensors are numbered in ascending order according to their position with respect to the interrogator, thus being FBG1 and FBG6 the closest and farthest sensors, respectively. The positions of the FBG sensors inside the mould are shown in Fig. 2(a).

The glass fibres in the experiment mainly consist of fibre bundles connected and fixed in a staggered way by binding ropes. The glass fibre bundle is also composed of many fibre strands with a diameter far smaller than the diameter of the bare optical fibre. The cross-section of the fibre bundle is shown in Fig. 2(c). Before the experiment, the upper and lower dies were locked with bolts and nuts to compress the GFRP samples, so that the optical fibre and FBG sensors remain tightly embedded in between GFRP layers. Then, the mould is placed on a heater, whose temperature is raised from room temperature (25°C) up to 55°C. After heating, the video camera is turned on to record the flow of silicone oil being injected by a high-pressure gun. Meanwhile, the time evolution of all FBG sensors is obtained at the sampling frequency of 100 Hz. Note that the density and viscosity of silicone oil are very close to the resin, but it will not cure the GFRP material. This is convenient for repeated comparison of experimental results. In this paper, silicone oil with a density of 955kg/m³ and a viscosity of 0.0191Pa·s is used as the injection fluid. The injection pressure is set to be 12Mpa, and the injection flow rate is about 45ml/s.

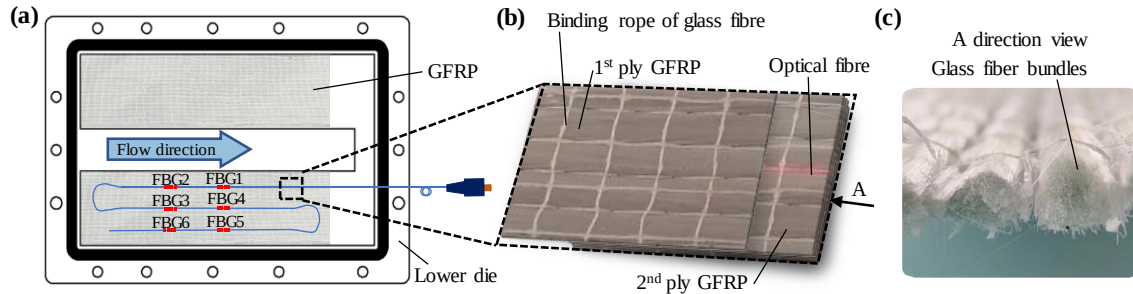


Figure 2. Experimental layout, showing (a) the position of FBG sensors, (b) GFRP plies superimposing, and (c) the glass bundles.

3. EXPERIMENTAL RESULTS

Fig. 3(a) shows the Bragg wavelength evolution of the six FBG sensors over time during injection process. Taking FBG1 as an example, it can be seen from the figure (cyan curve) that the process of silicone oil injection into the mould is divided into three stages: I. The first one is after mould locking and before injection; II. The second stage starts with the injection until the silicone oil reaches the sensor; III. In the last stage, the silicone oil flows over the FBG sensor and continues to move forward. All sensors experience the three stages, but just being time delayed according to the relative position of FBGs and the injection point. In the first stage, the optical fibre is embedded in the GFRP layers waiting for the silicone oil to flow, as shown in Fig. 3(b). This corresponds to the reference initial condition, indicating a zero-wavelength shift for the FBG. Then, in the second stage, silicone oil enters the mould and begins to soak GFRP material. Before the front of the fluid reaches the FBG sensor, the fluid with velocity pushes the optical fibre section with the FBG, as schematically illustrated in Fig.3(c). This results in an axial pushing effect over the FBG sensor, which leads to compressive axial strain on the sensor. However, due to the insufficient indirect force affecting the sensor, the central wavelength of the FBG decreases only slightly. It must be noted that this wavelength reduction can be observed in all sensors, but with different levels due to their positioning with respect to the injection point of the silicone oil. Then, when the fluid front arrives at the position of the sensor, as depicted in Fig. 3(d), the FBG sensor will be pulled by the fluid, resulting in a tensile axial force is applied to the sensor. However, while this tensile strain makes the Bragg wavelength of the sensors to increase, there is a simultaneous negative thermal change affecting the sensor, thus reducing the FBG wavelength. This is because the temperature of the silicone oil injected into the mould (at room temperature 25°C) is lower than the mould, which has been pre-heated to 55°C. This way, a significant sharp reduction of the FBG wavelength, dominating over the small tensile stress effect, is observed in the response of all FBG sensors. After the FBG is completely soaked into the fluid, the silicone oil will continue to move forward until reaching other FBG sensors.

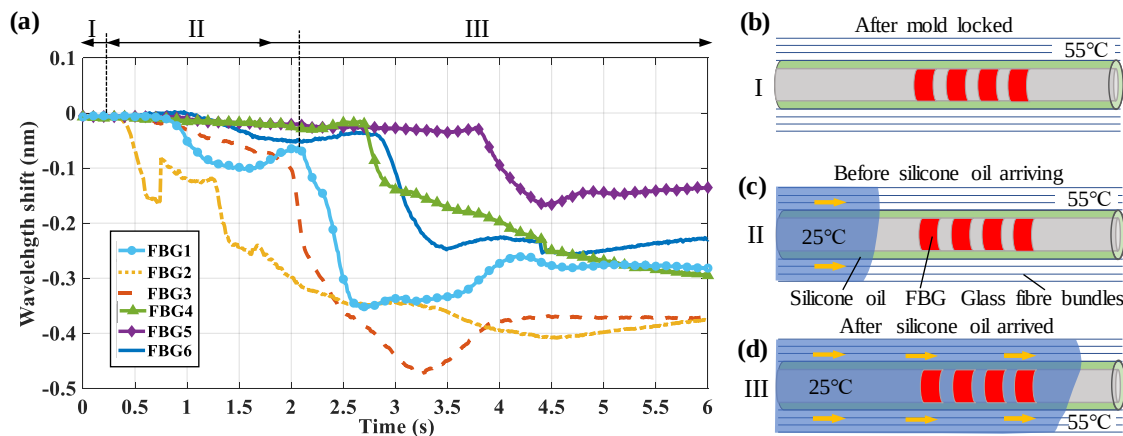


Figure 3. (a) Wavelength shift response of FBG sensors during silicone oil injection. Representation of (b) the first stage, before the fluid is injected into the mould, (c) second stage, when the oil flows in the mould but does not reach the FBG, and (d) third stage, after the fluid completely covers the FBG sensor and continue moving in the mould.

It is worth noting that the response time of the six FBG sensors depends on their positions in the mould with respect to the oil injection point. The fluid front can be determined by the moment when there is a sharp wavelength change in the

FBG response, which has been verified by images taken synchronously with a high-definition video camera, as shown in Fig. 4. The moment when the sharp Bragg wavelength reduces reflects the instant when the fluid front arrives at the FBG position inducing a sharp thermal change (see Fig. 4(a) for FBG3). As shown in Fig. 4(b), after 0.5 s the injection process starts, silicone oil has entered on the left side of the mould, where the GFRP sample and optical fibre are placed. Although the FBG3 has not been yet affected by lower silicone oil temperature, there is a small compression of the sensor due to the pressure induced by the silicone oil toward the right side of the sample. This results in a slight decrease in the FBG wavelength, as indicated by point A in Fig. 4(a). Then, as shown in Fig. 4(a) (point B), FBG experiences an abruptly wavelength reduction at 1.95 s, which corresponds to the moment that the silicone oil reaches the FBG, as can also be observed in the image captured by the video camera at that moment, as shown in Fig. 4(c). Comparing the recorded video images and the FBG measurements, results demonstrate that by detecting the sharp variation of the FBG wavelength, and knowing the FBG position, the flow front of the silicone oil can be identified in time and space.

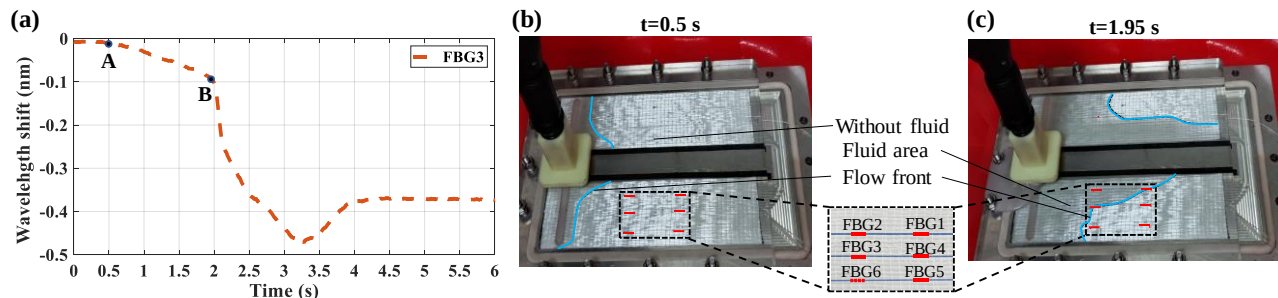


Figure 4. (a) Wavelength shift of FBG3 during silicone oil injection. Camera images at different moments: (b) 0.5 s and (c) 1.95 s.

4. CONCLUSION

In this paper, a method based on a series of FBG sensors has been proposed and validated to measure the flow front of resin injected into a closed mould during a HP-RTM process for manufacturing glass fibre composite materials. Comparing FBG measurements with camera images, experimental results have demonstrated that the flow front can be identified in time and space by detecting sharp thermally-induced FBG wavelength changes and knowing the position of a series of FBG sensors distributed throughout the mould. Based on this, the method requires no temperature-strain discrimination of the FBG measurements, whilst further research is still ongoing to develop an automatic detection of the moment of sharp wavelength change by using dedicated signal processing. Compared to other techniques, the small dimensions of the optical fibre make the proposed approach to be minimally invasive and can be used in-situ, embedding FBG sensors between glass fibres, where no other existing methods can be used.

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