Thesis abstract

„Monitoring of fiber reinforced polymers using fiber Bragg gratings inscribed in highly-birefringent optical fibers"

The main objective of the dissertation was to investigate the feasibility of effective use of embedded fiber Bragg gratings inscribed in highly-birefringent optical fiber (HB FBG) to measure strain during the manufacturing and exploitation stages of continuous fiber reinforced polymers and composite structures. Meanwhile, **the application goal** was to present ways to use HB FBG sensors in two selected modern composite manufacturing processes, namely resin transfer molding (RTM) and automated tape layup (ATL).

A thesis was stated, that the proposed generation of HB FBG sensors would allow the monitoring of the manufacturing processes of thermoset and thermoplastic matrix composites, as well as allow the measurement of the complex state of strain within the composite structure, both under quasi-static and time-varying loading conditions. It was concluded that the **following key tasks** were necessary to achieve the main objectives and prove the thesis of the dissertation:

- Building of a measurement system with fiber Bragg grating inscribed in a side-hole (SH) birefringent fiber,
- Application of HB FBG type fiber optic sensors for monitoring of a composite curing during the RTM process and for testing composites under bending conditions,
- The application of HB FBG sensors for monitoring composite fabricated by ATL process.

A review on the state of the art in fiber-reinforced composite monitoring, the sensors used for this reason and their integration techniques was conducted. The literature emphasizes that the anisotropic nature of composites, the diversity of their manufacturing techniques, and complex operating conditions make it challenging for monitoring systems to assess the service life, current health state and failure prediction in composite structures. Therefore, there is an observable trend towards the development of dedicated structural health monitoring (SHM) of the composite manufacturing process and the subsequent operation of composite structures. Moreover, it is known that advanced SHM systems consist of sensors deployed both on the surface and embedded inside the composite. Since the sensor are embedded at the composite production stage, the same sensors can also be used for process monitoring. There are various types of sensors, which can be used for SHM. Among them are fiber optics sensors, which shape and size allow them to be integrated into the structure without compromising the mechanical properties of the composite. Fiber optic sensors capable to measure strain, monitoring various phases of the manufacturing process were studied in more details. Among the various types of fiber optic sensors, fiber Bragg grating (FBG), including the continuously improving HB FBG, were considered particularly useful in composites research. As a result of the conducted literature review, a research program was formulated.

In the next step, the own research was conducted. The first part described the building of a measurement system with a sensor inscribed in a highly birefringent optical fiber. The required optical fiber was obtained and Bragg gratings were inscribed into it using the phase mask technique. These steps were possible thanks to the support of two research facilities in Lublin and Warsaw. Next, the sensitivity of the manufactured HB FBG sensor was determined, which required the construction of an original test setup and supporting software. Known parameters of a commercial sensor were used to calibrate the custom sensor. As a result, the full usefulness of the measurement system with the original HB FBG sensor for measuring strain along its length and across its diameter was demonstrated. The novel HB FBG had a significantly higher sensitivity to transverse force than sensors inscribed in a commercial fiber.

The second part focused on the application of HB FBG fiber sensors to monitor the thermoset composite curing kinetics during the RTM process and to test the manufactured composites under bending loads. First, it was necessary to investigate the effect of the compression occurring in the RTM steel mold on the sensor embedded in the reinforcing fibers and to evaluate the possible degradation of the sensor reflection spectrum. The next step was to study the curing kinetics of the RTM process by identifying the gel point and determining the complex strain state due to the resin curing process. The manufactured composite plates were then tested under quasi-static bending loads to demonstrate the ability of the HB FBG sensors to measure the complex strain state. As a result, it was demonstrated that embedded HB FBG sensors can be used to monitor the RTM process and measure the strain of thermoset composites produced by this process.

The third part dealt with the application of HB FBG sensors to monitor a thermoplastic composite produced by the ATL process. First, the effect of process temperature and roller compaction force on the measurement performance of FBG sensors had to be evaluated. Then, the residual strain state was measured in the plane of the composite plate, and in the perpendicular direction, both during the layup of subsequent composite layers and after the entire production process. It was thus possible to observe the cumulation of strain during the ATL process. In addition, strain was measured under cyclic loading conditions. It was shown that HB FBG sensors can be applied to observe the change in material stiffness and measure the area of the mechanical hysteresis loop. This allowed the study of local fatigue processes in composite structures.

In the final part of the dissertation, conclusions and remarks were formulated and directions for further research were identified.