Mechanical reliability of fiber Bragg gratings for strain or temperature sensor

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ABSTRACT

Several factors influencing the mechanical strength of fiber Bragg grating (FBG) sensors during their fabrication were examined and FBG sensors were made with sufficiently strong mechanical strength. A chemical stripping technique to remove the acrylate coating of the fiber and H_2 loading treatment to increase the photosensitivity showed negligible impact to the mechanical strength of fiber optic sensor. Therefore, these approaches were adopted for the discrimination of other factors pertaining to UV exposure. UV laser beam width exposed on the fiber was controlled up to 60 μm so as to reduce damaged areas induced from laser exposure. Also the pulse fluence and the total dose of a pulsed KrF excimer laser were varied in order to investigate their influence on the mechanical strength. Finally FBG sensors with different reflectivity were fabricated with only slight strength degradation such that they could be used in a composite structure.

Keywords: fiber Bragg grating, tensile strength, reliability, excimer laser, optical fiber.

1. INTRODUCTION

Fiber Bragg gratings (FBGs) are suitable for the health monitoring of aerospace and civil engineering structures as strain, pressure and temperature sensors. They can be easily embedded into composites with little effect on the mechanical strength of the host structures. They can also detect measurands at multi points by using wavelength division multiplexing in one sensor line [1,2]. In order to apply FBGs as reliable sensors in the commercial field, the reliability of the mechanical strength should be confirmed and the strain limit over the fracture of the host structure should be needed. Various parameters influencing the mechanical strength degradation of FBGs have been investigated and many researchers have attempted to develop techniques to reduce the damage in FBGs. These approaches include stripping methods [3], environmental humidity [4], pulse and total power of UV laser irradiation [5,6], wavelength of UV laser irradiation [7] and application of a coating material to the optical fiber [8,9].

In this work, factors that influence the mechanical failure strength of fiber Bragg grating sensors were analyzed. A technique relying on the reduction of the UV laser beam width was established to increase the FBG failure strength. The tensile strength of optical fibers was measured following application of stripping methods, H_2 loading treatment and several UV laser beam conditions. Finally, FBGs with different reflectivity were fabricated and the mechanical failure strength was measured.

2. EXPERIMENTAL SETUP

2.1 Dynamic tensile testing setup

A tensile testing set-up for the dynamic fatigue test was made according to the international standard IEC 60793-1-31. Optical fibers were wrapped three times over two mandrels with a diameter of 60 mm and one mandrel was moved outside to exert tension to the fiber. During the tension test, to prevent the slip of fiber and fiber damage at the joint part, the mandrels were coated with a 1mm thick layer of urethane. The gauge length was 150 mm. Constant velocity corresponding to strain rates of 5 %/min was used and the current load was measured from the load cell of the setup. Ambient conditions during the tensile test were maintained at $23\,°C$ and 50 % relative humidity. For each test, 10 to 20 samples were used.

2.2 Chemical stripping technique

Optical fibers are constituted of fused silica with 125 μm diameter and an acrylate coating layer having a roughly 250 μm outer diameter so as to provide mechanical protection and ensure survival in harsh environments. To make Bragg gratings in the fiber core, the coating should first be removed. Sulfuric acid was used, for the removing of the coating without affecting the fiber strength. Sulfuric acid was poured into a bowl and boiled to $190 \pm 10\,°C$ to remove the coating without leaving debris on the surface of the fiber [3]. The optical fiber was immersed into the hot sulfuric acid during a few seconds, and was then rinsed in water and acetone. During this treatment, care must be taken to ensure that the fibers do not contact each other or the surface of the bottle in order to prevent scratches and flaws on the surface of the fiber. If the fiber was broken, the sulfuric acid was replaced with a new solution so as to prevent contamination during the test.

3. RESULTS AND DISCUSSION

3.1 Influence of fiber stripping methods on the fiber strength

Experiments were performed to establish a stripping method that does not induce strength degradation. Figure 1 shows Weibull plots for pristine fibers, chemically stripped fibers and mechanically stripped fibers.

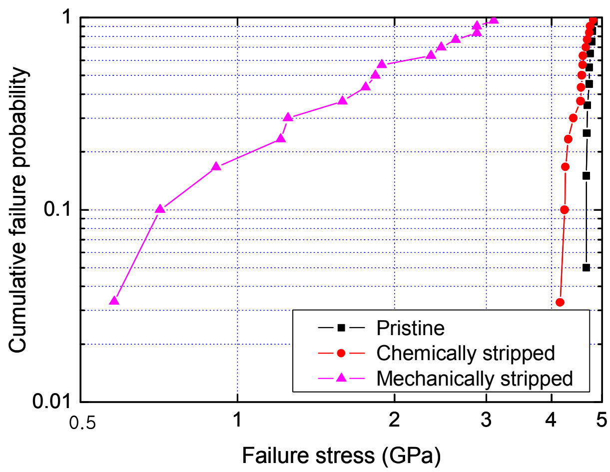


Fig. 1: Weibull plots for stripped fiber chemically and mechanically.

The mean failure strength of the chemically stripped fibers was 4.53±0.1 GPa similar to that of pristine fibers (4.73±0.04 GPa). All errors represent a 95 % confidence interval. These results verify that the chemical stripping method has little effect on the fiber when it is performed carefully. However, the mechanical stripping method resulted in decrease in the mechanical strength of the fiber to 1.87±0.42 GPa as a result of induced cracks and flaws on the surface of the fiber. The negligible mechanical strength degradation of the chemical stripping technique makes it possible to distinguish any possible degradation factor that might affect the Bragg grating fabrication. Thus, the chemical stripping technique was adopted for this study.

3.2 Influence of H_2 loading treatment on the fiber strength

In order to fabricate a Bragg grating in the fiber core by using a UV laser, the photosensitivity of the optical fibers should be enhanced. In this study, hydrogen loading treatment, a widely used technique, was employed at high pressures and temperatures [10]. The loading condition was 120 bar at $60\,°C$ for 1 week. The mean failure strength of pristine fibers and hydrogen loaded fibers were 4.73±0.04 GPa and 4.66±0.05 GPa, respectively. The result showed a similar trend to that of the chemical stripping method. Therefore hydrogen loaded fibers were used for the fabrication of Bragg gratings in order to verify the influence of other factors on the fiber strength due to UV irradiation.

3.3 Influence of UV laser beam width on the fiber strength

After chemical stripping to remove the fiber coating, the fiber was exposed to a KrF excimer laser (λ=248nm, MPB Co. Model ASX-750) running at a pulse rate of 50 Hz. In Figure 2, the exposed part of the fiber by the UV laser beam to inscribe the Bragg grating in the fiber is shown as a dark colored region. L is the gauge length and D is the beam width of the UV laser beam.

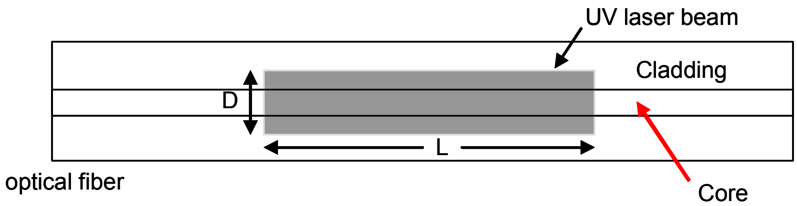


Fig. 2: Optical fiber exposed by UV laser

Standard single mode fibers consist of a core having a diameter between 4 and 9 μm and a cladding having 125 μm. To make a Bragg grating, a periodic refractive index variation should be inscribed in the core of an optical fiber by UV irradiation. However, laser exposure can induce fiber damage when too much energy absorbed from the UV beam to the fracture material structure is transferred to the material lattice [6]. Thus in order to reduce the extent of damage, the UV laser beam width exposed on the fiber was controlled to 60 μm and the gauge length was fixed as 10 mm. Table 1 summarizes the laser conditions, failure strength and m values obtained from this experiment.

Laser condition		N	Failure strength (GPa)				m
F_P (mJ/cm^2)	Beam width		Max.	Median	Min.	Mean	
No irradiation		10	4.83	4.74	4.67	4.73±0.04	94
100	60 μm	20	3.68	2.73	2.15	2.69±0.19	7
	2 mm	20	2.82	1.96	0.96	1.94±0.18	5
160	60 μm	20	2.75	2.2	1.83	2.17±0.11	10
	2 mm	20	2.44	1.62	0.83	1.61±0.23	3

Table 1: Summary of results for the UV irradiated optical fibers at various laser conditions

N is the sample number and m is the Weibull shape parameter. Pulse fluences (F_P) of the UV laser beam were changed from 100 mJ/cm^2 to 160 mJ/cm^2 while the total irradiated dose (F_T) was maintained at 100 J/cm^2. Figure 3 shows Weibull plots for the fiber irradiated with UV laser at different laser beam widths and F_P.

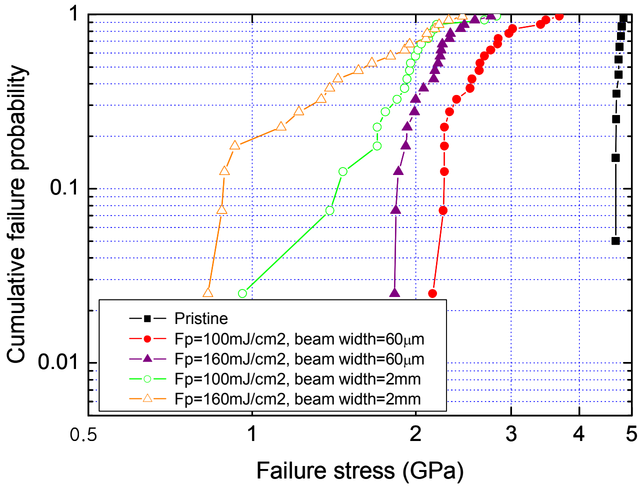
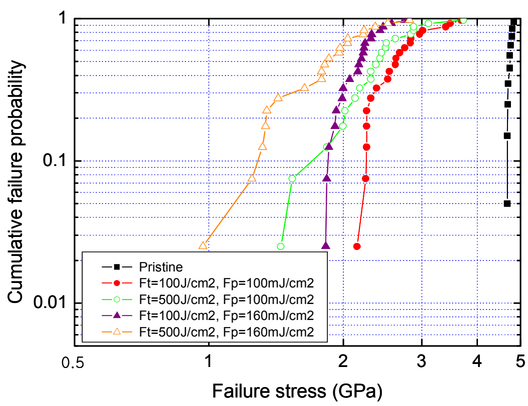


Fig. 3: Weibull polts for UV exposed fibers at different beam widths and F_P

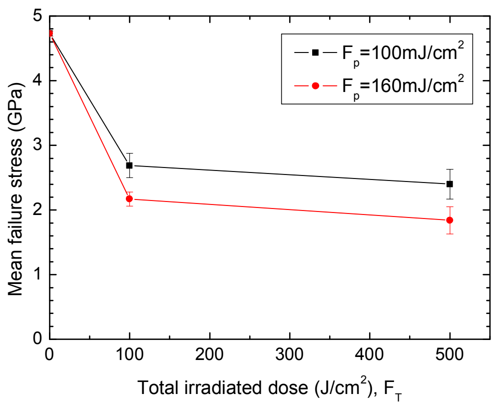
When the pulse fluence was 100 mJ/cm^2, the mean failure strength was increased by 39 % from 1.94$\pm$0.18 GPa to 2.69$\pm$0.19 GPa after the UV laser beam width was reduced to 60 μm. Similar results were obtained for a pulse fluence of 160 mJ/cm^2. The mean failure strength was increased to 2.17$\pm$0.11 GPa from 1.61$\pm$0.23 GPa, constituting an approximately 36 % improvement in mechanical strength. These results indicate that the induced failure stress degradation decreases with the decrease in UV laser beam width exposure on the fiber.

3.4 Influence of the pulse fluence and the total dose of UV laser on the fiber strength

The dependence of mechanical strength on both total irradiated dose and pulse fluence was investigated. Figure 4 (a) shows Weibull probability plots of UV irradiated optical fibers with different F_P and F_T.



(a)



(b)

Fig. 4: Weibull plots for UV exposed fibers at various laser conditions (a) and mean failure strength against the total irradiated dose (b)

The total irradiated dose was increased from 100 J/cm^2 to 500 J/cm^2 and pulse fluence was maintained at 100 mJ/cm^2 and 160 mJ/cm^2 respectively. The UV laser beam width exposed on the fiber was controlled to 60 μm and the gauge length was 10mm. The mean failure strength at a pulse fluence of 100 mJ/cm^2 was reduced from 2.69±0.19 GPa to 2.4±0.23 GPa when the total irradiation dose was increased from 100 J/cm^2 to 500 J/cm^2. Also, when the pulse fluence was 160 mJ/cm^2, the mean failure strength was reduced from 2.17±0.11 GPa to 1.84±0.21 GPa. Upon increasing the total irradiated dose, the failure strength was lowered, as shown in Figure 4 (b). Reducing the pulse fluence and the total irradiated dose was effective in increasing the mechanical strength of the UV exposed fiber.

3.5 Mechanical strength of FBG sensors with different reflectivity

Fiber Bragg gratings were fabricated using a phase mask method under a controlled UV laser beam width of 60 μm. The gauge length was 10 mm. A Weibull plot of the FBG sensors is shown in Figure 5 and the reflectivity of the FBGs, laser conditions and failure strength are summarized in Table 2.

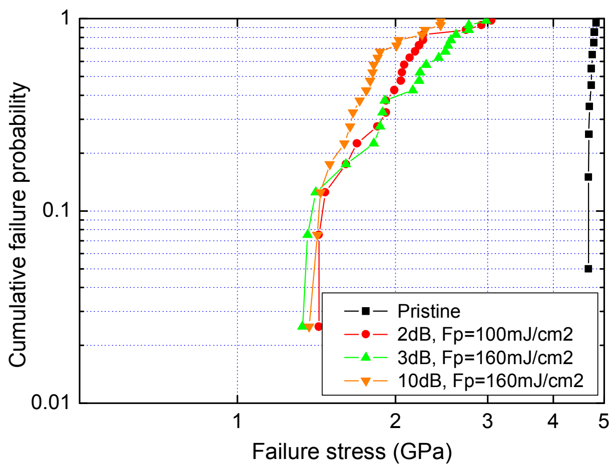


Fig. 5: Weibull plots for FBG sensors with different reflectivity

Reflectivity of FBG (%)	Laser condition		N	Failure strength (GPa)				m
	F_P (mJ/cm^2)	approx.F_T (J/cm^2)		Max.	Median	Min.	Mean	
37	100	470	20	3.05	2.09	1.43	2.06±0.2	6
50	160	110	20	2.98	2.19	1.33	2.16±0.22	5
90	160	340	20	2.44	1.86	1.37	1.83±0.14	7

Table 2: Summary of results obtained for FBG sensors.

When the pulse fluence was 100 mJ/cm^2, FBGs having only 37 % reflectivity were fabricated until the total irradiated dose was increased up to 470 mJ/cm^2. The mean failure strength was 2.06±0.2 GPa. In order to make strong gratings, the pulse fluence was increased to 160 mJ/cm^2. The mean failure strength of FBGs with 50 % and 90 % reflectivity was 2.16±0.22 GPa and 1.83±0.14 GPa, respectively. In order to use an FBG as a strain or temperature sensor, generally Bragg gratings with more than 50 % reflectivity, i.e., strong gratings, are needed so as to increase the signal to noise ratio and transmit the signal over a long distance. In this experiment strong gratings with sufficient mechanical strength for use in composites were fabricated.

4. CONCLUSIONS

In this study, several factors influencing the mechanical strength of FBGs have been tested. The negligible mechanical strength degradation of the chemical stripping technique and H_2 loading treatment was verified. In order to reduce damaged regions, the UV laser beam width exposed on the fiber was controlled to $60\,\mu m$. As a result, the mechanical strength was increased by 39 %. Also experiments showed that increasing both the pulse fluence and total irradiated dose induced mechanical strength degradation. Finally, FBGs with high reflectivity were fabricated and showed sufficiently high mechanical strength. The mean failure strength of FBGs having 90 % reflectivity and 10mm guage length was 1.83 ± 0.14 GPa.

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