1 Introduction
Fast and low-cost manufacturing technologies of large and complex-shaped FRP structures have become developed for consumer applications such as automotives. In the development of a molding technology, it is important to estimate accurate degree of curing progress and residual strain of FRP. Therefore, many real-time cure monitoring systems have been developed using in situ sensors. Among these sensors, implantable fiber optic sensors are promising to measure material properties of FRP structures during molding due to thin fiber shape, flexibility, high strength and high sensing function. Consequently, many kinds of fiber optic sensors have been proposed [1]. However, it cannot be said that they offered sufficient systems for manufacturers yet.

Monitoring methods of FRP molding process using fiber optic sensors are a measurement technique of cure index using an infrared absorption spectrometer [2-5], strain measurement techniques using an EFPI (Extrinsic Fabry-Perot Interferometer) strain sensor and an FBG (Fiber Bragg Grating) sensor [6-9], and a cure monitoring technique by fiber-optic refractive index measurement [9-12], etc. A fiber-optic infrared spectroscopy-based cure monitoring is a method to estimate molecular structures by measuring infrared absorption spectrum of reactive molecules of resin. Although this technique is able to monitor progress of cure reaction in detail, it is difficult to measure cure index accurately due to large noise. Strain measurement techniques can used to measure shrinkage by cure reaction and thermal strain by heating or cooling. Both a fiber-optic spectrometer and a fiber-optic strain sensor are effective to process monitoring, however the sensors and measurement systems are very expensive.

On the other hand, a refractive index measurement method, which is a technique to measure cure index of resin from Fresnel’s reflection at interface between glass fiber and resin, is inexpensive due to simple optical system. The authors have been proposed cure monitoring methods using optical fiber sensors such as a fiber optic refractive-index measurement method an EFPI strain sensor and FBG strain sensors. A refractive-index measurement method has been proven to be applicable to monitor progress of cure reaction of resin form start to finish [12]. On the other hand, it is shown that EFPI and FBG strain sensors can measure thermal and cure-shrinking strain during cure process [9].

In the present study, we aim to develop a process monitoring systems for monitoring cure index and strain during molding of FRP laminates. Both FBG and refractive-index sensors are used as fiber optic sensors for the system and dual light sources are employed to obtain two measurement values from single sensor. The developed system was applied to monitor hot-press molding process of GFRP laminates.

2 Process monitoring by fiber optic sensors
2.1 Refractive index sensors
Figure 1 illustrates schematic views of a refractive-index sensor. The sensor utilizes Fresnel’s reflection at the end surface between an optical fiber (glass) and resin. Since the sensitivity of refractive index of resin is much larger than that of silica glass during molding process, the variation of refractive index of resin contributes change in reflection rate. Therefore, refractive index of resin can be obtained from reflected optical intensity. In the present paper, we evaluate refractive index variation $\Delta n$ from the standard value of refractive index $n_s$ as follows.

$$I = \Delta I + I_s, \text{ when } n = \Delta n + n_s, \quad (1)$$
where $n$ is refractive index of resin, $I$ is measured optical intensity of a reflected light, $\Delta I$ is variation of the measured optical intensity from the standard optical intensity $I_s$. The $\Delta n$ can be calculated from $\Delta I$ by the following simple equation.

$$\Delta n = \frac{h_1 \left( a_1^2 b_2 (h_1 + b_1) + a_2^2 h_1^2 \nu \pm a_1 (h_1 + b_1) \sqrt{a_1^2 b_2^2 + a_2^2 h_1^2 \nu^2} \right)}{a_1^2 (b_1^2 - b_2^2) - a_2^2 h_1^2 \nu}$$  

(2)

$$a_1 = n_g + n_{air}, \quad a_2 = n_g - n_{air},$$  

$$b_1 = n_g + n_r, \quad b_2 = n_g - n_r, \quad \nu = \Delta I / I_{air}$$  

(3)

where $I_{air}$ is reference optical intensity of reflected light from the air, $n_g$ is effective refractive index of an optical fiber, $n$ is refractive index of resin, and $n_{air}$ is refractive index of the air. It is supposed that $n_s$ is already known.

Figure 2 shows a typical relationship between refractive index and temperature of epoxy resin during cure process. It is well known that refractive index of materials has temperature dependency. The temperature dependence curve shifts when cure reaction proceeds as shown in Fig. 2. Therefore, we can estimate cure index from refractive index. In the present paper, we did not calculate cure index of GFRP laminates because cure index of B-stage prepreg is unknown.

### 2.2 Refractive index measurement of particle dispersed polymers

When particles such as fillers or micro air bubbles disperse in resin, it can be considered that the optical output is affected by lights scattering back from the particles as well as Fresnel reflection as illustrated in Fig. 3. When light is incident on the reflection surface between an embedded optical fiber and resin, most light power leaked into resin. Some of the leak light is reflected by the particles and reentered into the optical fiber. Since the intensity of back-scattered light is almost the same as that of the Fresnel reflection due to small mismatch of refractive index between glass and resin, the scattered lights produce interference signal.

Here, we suppose that lights back-scattering from $N$'s particles reentered into the optical fiber. When a

monotonic light $v_0$ is incident to the reflection surface, reflected light can be written as follows:

$$v(t) = v_0 \left( r e^{i\omega t} + \sum_{i=1}^{N} r e^{i\omega (t - z_i)} \right),$$  

(4)
where \( r \) is reflection rate of amplitude of Fresnel reflection, \( r_i \) and \( \tau_i \) are reflection rate of amplitude and phase delay of the \( i \)th back-scattering light and \( \omega \) is angular frequency of incident light. From the equation (7), optical output \( I \) becomes

\[
I = I_0 \left( r^2 + 2r \sum_{i=1}^{N} r_i \cos \omega \tau_i + \sum_{i=1}^{N} r_i^2 \right) + 2 \sum_{i=1}^{N} \sum_{j=1}^{N} r_i r_j \cos \omega (\tau_i - \tau_j) \] ,
\]

where \( I_0 \) is optical intensity of the incident light. When a white light is used as a light source, the interference terms of equation (5) disappears and thus the following equation is driven.

\[
I = I_0 \left( r^2 + \sum_{i=1}^{N} r_i^2 \right) ,
\]

This indicates that effect of the back-scattering light in the equation (6) is much less than that in the equation (5). In the present study, a SLD (Super Luminescence Diode) broad-band light source is employed for a refractive index measurement system, and a narrow-band light source for a process monitoring system which measures refractive index and strain simultaneously.

2.3 FBG sensors

An FBG sensor summarized in Fig. 4 is a narrowband filter-based sensor. This sensor has periodical distribution of refractive index which works as Bragg grating in a core of fiber. When broadband light is incident into the Bragg grating part, narrowband light returns. The reflected light has a center wavelength \( \lambda_B \), which is called Bragg wavelength. It is well known that shift of Bragg wavelength \( \Delta \lambda \) is proportional to axial strain \( \varepsilon_3 \) and temperature variation \( \Delta T \) of optical fiber. The relationship between the wavelength shift, strain and temperature variation, which has been measured by our laboratory, is written as

\[
\frac{\Delta \lambda}{\lambda_0} = 0.7368 \times (\varepsilon_3 - 0.5 \times 10^{-6} \times \Delta T) + 6.9032 \times 10^{-6} \times \Delta T,
\]

where \( \lambda_0 \) is the initial Bragg wavelength.

2.5 Process monitoring system for simultaneous measurement of refractive index and strain using dual light sources

The process monitoring system used in this study for simultaneous measurement of refractive index and strain is shown in Fig. 5. This system employed two light sources of narrow band FP-LD (1310nm) and broadband SLD (1550nm center wavelength). The two lights are combined by a WDM coupler (1300/1550), and the coupled light travels into a sensing fiber through an optical circulator. The sensing fiber has one FBG sensor and the end surface is cut flat. An FBG sensor reflects only the light of the Bragg wavelength, and the transmitted light with a notched spectrum reflects at the interface of optical fiber (glass) and resin by
Fresnel’s reflection. The light traveled back again through a circulator is separated into 1300nm band and 1500nm band, and the former is sent to an optical power meter, the latter to an optical spectrum analyzer (OSA MS9710B Anritsu Co. Ltd.).

3 Materials and experimental systems

3.1 Hot-press molding of GFRP laminates

In the present study, molding process of GFRP unidirectional laminates by a hot-press molding method was monitored. Twelve sheets of GFRP prepreps (GE352G135SB Mitsubishi Rayon Co. Ltd.), which were 120μm thick, were stacked in the same direction on an aluminum flat plate. The optical fiber sensor was embedded in the middle layer of laminates. The laminate was heated from room temperature up to 140°C in 70 minutes and cured for 3 hours by a hot-press machine. When temperature reached 60°C, molding pressure of 0.5MPa was applied and held until the end of the molding.

3.2 Experimental system using SLD light source for refractive index measurement

Two optical fibers and a SLD light source were used in refractive index measurements as illustrated in Fig. 6. The light from the source was divided into two paths by a 2x2 coupler. The intensity of reflected lights was measured by two photo detectors (PD) individually. A thermocouple was also used for measuring temperature inside of laminates. All data from the sensors were recorded by a personal computer at 1 Hz.

Location of optical fiber sensors were shown in Fig. 7. One sensor was embedded in 0° direction of the laminate. In order to investigate effect of reinforcing fibers on measurement ability of the sensors, another sensor was embedded in resin which was flown out from prepreg by cutting a corner of the laminate as shown in Fig. 7(a). In another experiment, sensor was also embedded in 90° direction of the laminate as shown in Fig. 7(b) for investigating effect of reinforcing direction of laminates on refractive index of prepreg resin.
3.3 Experimental system using dual light sources for process monitoring

The optical fiber has the FBG sensor part and the refractive-index sensor part. The experimental set-up using dual light sources for process monitoring was illustrated in Fig. 8. In this system, 1310nm narrow-band FP-LD (Fabry-Perot Laser Diode) and SLD of 1550nm (C-band) were employed as light sources. Both lights were coupled through a WDM coupler. The coupled lights were incident into the refractive-index and FBG sensors, and then the reflected lights were divided into 1310nm band and C-band by a WDM coupler. The 1310nm-band light was measured by an optical power meter and the C-band light was, by an optical spectrum analyzer for obtaining refractive index and strain of FRP, respectively. The embedded thermocouple was also used for measurement of temperature. Figure 9 shows location of fiber optic sensors embedded in GFRP laminates. All sensors were embedded between 6 and 7 layers.

3 Experimental results and discussions
3.1 Monitoring by refractive index measurement system using SLD light source

Figure 10 shows relationship between optical intensity measured by the refractive index measurement system using SLD light source, temperature and molding cycle time during molding of the GFRP laminates. The red line indicates optical intensity from the sensor embedded in FRP laminate and the blue line, in resin. The initial values of optical intensity indicate Fresnel’s reflection at interface between optical fiber and air because the intensity did not vary when optical fibers were embedded. In addition, the intensity did not vary by vacuuming and applying molding pressure. Therefore, it appeared that the air void existed around the sensor in laminates tip at room temperature before starting molding process. Intensity of the sensor in FRP dropped suddenly at 90°C. The reason of this rapid decrease is considered that the tip of the optical fiber contacted with the resin. On the other hand, the optical intensity of the sensor in resin suddenly fell down at 110°C. From behavior of the temperature curve around 100°C, it was found that heat absorption occurred by melting of prepreg resins. Therefore, these results show that

Fig.8 Process monitoring system for measuring refractive index and strain of FRP laminates using dual light sources.

Fig.9 Location of sensors embedded in laminates for the experiment using dual light sources.

Fig.10 Relationship between optical intensity, temperature and molding cycle time during molding of laminates (SLD light source).
preg resin flows by applying pressure below the melting temperature.

After the sensor tip was covered with resin, refractive index was calculated from the optical intensity using the equation (2). Relationships between refractive index variation, temperature and molding time were plotted in Fig. 11. The first ordinate is refractive index variation $\Delta n$ from the value at the end of cure process. From the figure, it was shown that the $\Delta n$ curve of the sensor in FRP had large fluctuation from 30 to 45 minutes. This fluctuation is thought to result from the effect of scattered lights from air voids as illustrated in Fig. 2. When the micro air voids exit near the end surface of optical fiber, a transmitted light from the optical fiber scattered by the voids and some scattered lights entered back into a core of the fiber as represented by the equation (6). The fluctuation disappeared after 45 minutes because the air voids disappeared by vacuuming process. These results show that the refractive index sensor could be used for monitoring air voids in laminates qualitatively.

The $\Delta n$ tended to decrease linearly with temperature increase from 30 to 45 minutes. It is well known that this decrease is temperature dependency of refractive index. However the $\Delta n$ turned to increase but temperature was increasing after reached the minimum value at 45 minutes. This reason was that proceeding of cure reaction increase refractive index. Therefore it appeared that the prepgs used in this study started cure process at 110°C as soon as melted. The $\Delta n$ curve almost converged at 70 minutes.

Figure 12 shows relationship between refractive index variations measured by sensors embedded in 0° and 90° directions, and temperature during molding of laminates. From the figure, it was found that the $\Delta n$ curves of 0° and 90° were similar to each other until cure reaction completed at 140°C. This means that effect of reinforcing fibers on cure monitoring by refractive index measurement is small. However, when cooling resin, $\Delta n$ curves of 0° and 90° were different from each other. This reason is thought to be that orthotropic thermal stress affected refractive index of resin strongly during cooling due to high stiffness of cured resin. These results suggest that we can conduct quantitative measurement of cure index of FRP laminates by this method.

**3.2 Monitoring results by process monitoring system using dual light sources**

In this experiment, both refractive index and strain were measured by a process monitoring system using dual light sources.

Relationship between optical intensity from refractive index sensor, temperature and molding cycle time during molding of laminates is shown in Fig. 13. In comparison of this graph to Fig. 10, it was found that optical intensity by the process monitoring system using dual lights was much less than that by the refractive index measurement system using a SLD light because most power of SLD light was attenuated by WDM coupler in the
process monitoring system. However, behavior of reflected intensity was similar to the results plotted in Fig.10. Then it appeared that the resin flow could be also monitored qualitatively by this system. Refractive index variation $\Delta n$ obtained by the process monitoring system and temperature were plotted against molding time in Fig.14 with results in Fig.11. The red line indicate $\Delta n$ curve by the refractive index measurement system using SLD and the blue line, the process monitoring system using dual lights. From the figure, it was found that both $\Delta n$ curves had similar behaviors to each other however the $\Delta n$ curve by the system using dual lights showed larger fluctuation. The reason is thought to be that a narrow FP-LD used in the process monitoring system produced interference signals as described in the equation (5). The large error generated by interference should be minimized for measurement of cure index by improvement of an optical system in future. For example, this interference can be eliminated if a broad-band light around 1310nm is employed.

Figure 15 shows the relationship between strain measured by the system using dual lights, temperature and molding cycle time during molding process. From the results, it appeared that the strain increased linearly with temperature increase until 19 minutes by thermal expansion of prepregs. However, it was seen that the wavelength suddenly jumped by 400 $\mu\varepsilon$, when the temperature reached 60°C at which molding pressure was applied. Although some of the increased strain caused by heating and molding pressure was relaxed, 500$\mu\varepsilon$ remained when the prepreg resin melted at 100°C. The remained tensile strain during molding process may affect residual strain of fibers after manufacturing. From the above results, it appeared to be possible to monitor internal strain caused by molding temperature and pressure during a hot-press molding of FRP laminates by the present process monitoring system.

4 Conclusions

At first, we applied a refractive index measurement system using SLD light applied to process monitoring of GFRP laminates. From the experimental results, it appeared that refractive index of prepregs could be measured quantitatively
without effect of reinforcing fibers. In addition, initiation of air voids in laminates could be monitored qualitatively. Secondly, a process monitoring system by combining FBG and refractive index sensors were developed and applied to process monitoring of FRP laminates. The experimental results showed that the strain and refractive index of prepregs could be monitored simultaneously. For more precise measurement of cure index, an optical system of the process monitoring system will be improved in future.

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References