Comparison of nondestructive microfailure evaluation of fiber-optic Bragg grating and acoustic emission piezoelectric sensors using fragmentation test

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Abstract

Nondestructive evaluation of microfailure mechanisms in two-dimensional SiC fibers/epoxy composites is investigated using a directly embedded fiber-optic sensor attached with an acoustic emission piezoelectric (AE-PZT) sensor. Interfacial shear strength by fragmentation test, and optical failure observation inside microcomposite can contribute to analyze two sensors quantitatively. Although fiber Bragg grating (FBG) sensor exhibits sudden wavelength shift due to plastic deformation by larger diameter SiC fiber breakage, AE-PZT monitors much more precise microfailure process, such as the fiber break or matrix cracking. Since the FBG sensor can measure the strain at only a single point, whether it can detect a fiber break in single-fiber composite specimen depends on its proximity to the failure location. In addition, micro-strain measurement at one single point may not provide enough information on the whole microfailure process including multiple fiber breakage and matrix crack. It can be considered that FBG sensor can be somewhat effective in measuring the continuous micro-strain change due to the internal disturbance such as resin curing, whereas AE-PZT sensor can be effective in detecting the microfailure by elastic wave propagation through the composite materials.

Keywords

B. Fragmentation; B. Interface/interphase; C. Micro-mechanics; D. Acoustic emission

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Abstract

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1. Introduction

Recently, several studies on the curing characterization and on the failure behavior of composite materials using a fiber-optic sensor technique have been performed due to its various advantages compared to other sensors [1–4]. However, there are few works on the microscopic evaluation of failure mechanisms of the composite materials in a quantitative, rather than qualitative manner using above sensors. With a fiber-optic sensor embedded in the composite structure, in situ curing state or health monitoring during the manufacturing process and service period of the structure can be monitored continuously [2,3].

Acoustic emission piezoelectric (AE-PZT) sensor, a polycrystal compound of lead zirconate and lead titanate, has been commonly used for detecting the generation or the propagation of micro-defects such as micro-crack and micro-failure in a composite material. In contrast to the ordinary PZT sensor attached to the outside surface of the structures, a fiber-optic sensor does not to be influenced by the electromagnetic field [5]. Since the fiber-optic sensor has some beneficial properties such as low specific weight, fiber-like small size, and good compatibility with polymeric composites, the fiber-optic sensor can be used in cure and health monitoring of composite materials. Especially, fiber Bragg grating (FBG) sensor has competitive advantages compared to other fiber-optic sensors as follows [6]: (a) absolute measurement, because the sensed information is encoded directly into wavelength, the output does not
depend on the total light levels, losses in the connecting fibers and couplers or source power; (b) the FBG sensor output is linear function of strain; (c) inherent high strength.

Microscopic measurement of interfacial shear strength (IFSS) between fiber and matrix is an important factor to study the macroscopic behavior of the composite material. To evaluate the interfacial adhesion of composites, the dogbone-type microcomposite fabricated with single or multi-fibers embedded in epoxy matrix have been used for the micromechanical tests. Some conventional characterization techniques for IFSS include the single-fiber microdroplet test [7,8], fragmentation test [9–11] and microindentation test [12]. The single-fiber microdroplet test (also known as the single-fiber pullout test) is considered as a very convenient method for the direct measurement of IFSS because it is not limited by the properties of the fiber and matrix except showing the data scattering. The fragmentation test, also called as single-fiber composite (SFC) test, has been used for many thermosetting epoxy composites [9–11] and thermoplastic composites [13–15].

The SFC technique, originally proposed by Kelly–Tyson [16] for the ceramic fiber reinforced metal matrix composites, can provide abundant statistical information about the interfacial failure mode as well as reliable IFSS using only a few microcomposite. Drzal [17,18] performed many fragmentation tests for fiber reinforced polymer composites by a specially designed tensile machine under a polarized-light microscope. Two Weibull parameters for average fiber fragment length and fiber tensile strength are combined to calculate the meaningful IFSS statistically. Subramanian [19,20] used lognormal distribution with two parameters to consider critical aspect ratio of fiber fragment and fiber tensile strength. Phoenix [21,22] developed Drzal system further using Monte-Carlo method.

Quantitative evaluation of detection of transverse cracks using embedded FBG sensors was investigated for laminate CFRP composites [23]. Main objectives of this work are to evaluate quantitatively and to compare the sensing characteristics simultaneously through fragmentation technique using an identical microcomposite with an embedded FBG sensor and an attached AE-PZT sensor on one side of the specimen.

2. Experimental

2.1. Materials

2.1.1. Fiber and matrix

Two kinds of SiC fibers are used in this study. One is SiC fiber of 13.6 μm in diameter (called as Nicalon fiber, Nippon Carbon Co., Japan) and another is SiC fiber of 137 μm in diameter (SCS-6, Textron Co.). A typical composition of a Nicalon fiber is 58.3%-silicon, 30.4%-carbon and 11.1%-oxygen by weight basis. A Nicalon fiber is extracted from a tow consisting of 500 filaments and 137 μm SiC fiber is extracted from continuous woven preform sheet, and they are used without further treatment. YD-128 Epoxy resin (Kukdo Chemical Co., Korea) based on diglycidylether of bisphenol-A and Jeffamine D400 and D2000 (Huntsman Petrochemical Co.) curing agents based on polyoxypropylenediamine are used for the fabrication of microcomposite. To obtain the appropriate epoxy matrix with optimized ductility for the test, adjusting relative proportions of D400 versus D2000 in the curing mixture controls the flexibility of the specimens. The epoxy resin mixture with curing agents is precured for 2 h at 80 °C and then postcured for 1 h at 120 °C in a dogbone specimen mould.

2.1.2. Fiber-optic sensor

In Fig. 1, a fiber-optic Bragg grating can be made by producing periodic variation in the refraction index along a short section in the core of a fiber-optic [24]. The grating creates a filtering function within the fiber-optic such that the waveguide reflects only a narrow wavelength band from the whole broad wavelength range of the incident light source. Two types of fiber-optic sensors from 3M (U.S.A.) and Innovative Fibers (Canada) were used. Bragg wavelength of FBG sensor for 3M and Innovative Fibers in the standard state were 1291 and 1534 nm, respectively, in the infrared range. Detailed properties of two fiber-optic sensors are shown in Table 1. A fiber-optic contains the bare sensor in the center part coated with polyimide for protection.

![Fig. 1. The structure and measurement principle of FBG sensor.](image-url)
Table 1
Characteristics of two FBG sensors

<table>
<thead>
<tr>
<th>Index</th>
<th>3M Innovative fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grating type</td>
<td>FBG-1291</td>
</tr>
<tr>
<td>Grating number</td>
<td>–</td>
</tr>
<tr>
<td>Center wavelength (nm)</td>
<td>1291</td>
</tr>
<tr>
<td>FWHM (nm)</td>
<td>&gt;0.2</td>
</tr>
<tr>
<td>Peak reflectivity (%)</td>
<td>70</td>
</tr>
<tr>
<td>Fiber type</td>
<td>–</td>
</tr>
<tr>
<td>Fiber pigtail (m)</td>
<td>–</td>
</tr>
</tbody>
</table>

Light source with wide range can be inserted to the one end of the fiber-optic. Some of the incident light can be reflected and the partial portion of ray can be also transmitted. The wavelength of the reflected light is related to the spacing of the index perturbation of the grating and the effective refractive index (ERI), \( n_e \) of fiber-optic core material to form a following relationship

\[
\lambda_B = 2n_e \lambda
\]

where \( \lambda_B \) is Bragg wavelength satisfied with Bragg grating condition, \( \lambda \) is lattice spacing and \( n_e \) has the value of 1.46 for fiber core material. When the external disturbance such as micro-strain or temperature change are applied to fiber-optic sensor, the changes of ERI and lattice spacing result in the shift of the peak value of the Bragg wavelength.

For measuring the change of Bragg wavelength, the degree of external disturbance can be obtained theoretically as follows

\[
\Delta \lambda_B = \lambda_B \left[ (\alpha + \xi) \Delta T + (1 - p_e) \Delta e \right]
\]

where \( \Delta T \) is a temperature change and \( \alpha \) is a thermal expansion coefficient for silica core. The quantity \( \xi \) represents the thermo-optic coefficient. \( p_e \) is an effective photoelastic constant having a value of 0.22 for a silica core material [6].

A FBG sensor can be used directly as a strain sensor as well as a temperature sensor. When the fiber is mechanically strained with no change of temperature accompanied (\( \Delta T = 0 \)), the Bragg wavelength varies due to the change in the grating spacing.

For instance, wavelength changes due to the application of the same amount of 1000 \( \mu \)strain are to be about 1 and 1.17 nm for the sensors with Bragg wavelength of 1291 and 1534 nm, respectively [25].

In this case the fractional change in Bragg wavelength for longitudinal strain by the external disturbance such as a fiber break as follows [6]:

\[
\varepsilon = \frac{\Delta \lambda_B / \lambda_B}{(1 - p_e)}
\]

2.2. Methodologies

2.2.1. Single-fiber strength measurement

Tensile strengths of 13.6 \( \mu \)m SiC fiber are measured for the five gauge lengths of 2, 5, 10, 20 and 100 mm, respectively. While the tensile strengths of 137 \( \mu \)m SiC fiber are measured for three gauge lengths of 10, 20 and 40 mm, because of experimental limitations due to thick diameter for the latter case. A single fiber is placed on the paper frame and then temporarily fixed by Scotch tape in the center on both ends. Epoxy adhesive is used to fix a fiber on the paper frame and then cured for 12 h at room temperature. Average diameters of 50 SiC fibers were measured by an optical microscope (HEX-DX, Nikon Co., Japan) attached with calibrated eyepiece lens. Tensile strength of single fiber is measured at the crosshead speed of 0.5 mm/min using the universal testing machine (UTM) (LR-10K, Lloyd instruments Ltd, U.K.) equipped with 100 N load cell.

2.2.2. Preparation of microcomposite specimen

Dimensions of 1 mm in thickness, 3 mm in width, 25 mm in gauge length and 45 mm in full length of the dogbone shaped specimen are shown in Fig. 2. Two SiC fibers with different diameters and one fiber-optic are fixed in the same silicone rubber mould with dogbone shape. Modified epoxy resin is poured into the mould and cured at 80 °C for 1 h and then postcured at 120 °C for 2 h. To obtain an optimum testing condition avoiding catastrophic failure of the specimen before ending the test, due to the brittle nature of the matrix, epoxy resin is modified by adjusting the ratio of various curing agents. Tensile properties of neat epoxy specimen without fiber are measured from the stress–strain curve. Crosshead speed of 1 mm/min is chosen for the test by UTM with 1 kN load cell.

2.2.3. Measurements of IFSS

To measure IFSS for the microcomposite of dogbone type embedded with two SiC fibers, a specially designed mini-tensile machine is used under a polarized-light microscope. To set up the microcomposite on the mini-tensile machine, uniaxial tensile load is applied with monotonically increasing fashion. The microfailure modes of the specimen are observed simultaneously. With increasing the load, corresponding tensile load is transferred to the fibers via modified epoxy matrix, which results in the increase of the fiber breaking number in the specimen. Load is applied until the fiber break no longer occurs, and then critical fiber fragment length, \( l_f \), is measured under an optical microscope equipped with calibrated eyepiece lens. The classical relationship between fiber tensile strength, \( \sigma_f \), critical fiber fragment length, diameter ratio (i.e. aspect ratio, \( l_f/d \)) and IFSS, \( \tau \) is given by Kelly–Tyson [16] as follows:

\[
\tau = \frac{\sigma_f d}{2l_f}
\]

Drzal [17] altered Kelly–Tyson equation (4) to introduce the statistical meaningfulness by combining with Weibull distribution. The modified IFSS is given in terms of
Gamma function and statistical parameters as follows:

$$\tau = \frac{\alpha}{2\alpha} \Gamma \left[ 1 - \frac{1}{\beta} \right]$$

(5)

where $\alpha$ and $\beta$ are scale and shape parameters, respectively, and $\Gamma$ is Gamma function. A direct tensile test to find fiber strength at the critical fragment length (usually less than 1 mm) can result in the experimental difficulties. After fiber strengths are commonly determined at measurable gauge lengths, they are subjected to be with subsequent extrapolation to smaller gauge length using Weibull weakest link rule [26]. Tensile strength at such a critical fragment length can be obtained as follows:

$$\sigma_l = \sigma_0 \left( \frac{l_0}{l_c} \right)^{-1/\rho}$$

(6)

where $\sigma_0$ is the fiber strength at gauge length $l_0$ and $\rho$ is the shape parameter of Weibull distribution for fiber strength.

2.2.4. Microfailure detection via FBG and AE-PZT sensors

To characterize the microfailure mechanisms by detecting the occurrence of microfailure of fibers under the tensile load, Bragg wavelength change, AE signal, and strain can be used simultaneously using the same specimen. Fig. 3 shows the systematic and integrated setup diagram for the tensile test for microfailure detection. Since the size of dogbone specimen is relatively small and precise as shown in Fig. 2, a designed mini-tensile machine is used. There is no special controlling device for the crosshead speed. Instead of measuring the load value, the displacement of the gauge length part is only recorded using an attached displacement sensor.
dial gauge. The recorded displacement can be easily converted to the corresponding strain of the specimen by simply dividing by the initial gauge length. Strain gauge is also attached underneath the bottom of the specimen and connected to strain amplifier and RMS voltmeter. A fiber-optic sensor is positioned parallel to two SiC fibers, whereas AE sensor is attached on the center and top surface of the specimen. It is noted that the covering length of the AE sensor is 15 mm in the 25.4 mm gauge length of the specimen.

The output of LED is stabilized against drift in output power and changes in spectral characteristics, using a laser diode controller, so that the interpretation of sensor data is free from associated errors. The coupler is a standard fiber-optic component that is used as a beam splitter in the sensor system. It separates the input light used to illuminate the fiber sensor string from the light reflected by the FBG sensor. Bragg wavelength reflected from the fiber-optic sensor is analyzed using an optical spectrum analyzer (OSA, Model Q8381A, Advantest Co.) and personal computer to provide faster response for use in real-time data acquisition during testing.

AE analysis is also performed using AEDSP analyzer (Mistras 2001, Physical Acoustics Co.), true RMS voltmeter (HP 3400A) and digital storage oscilloscope (LeCroy 3504A). AE-RMS voltage and strain gauge data can be read at the sampling time of 0.5 s and they are displayed at the same time. The correlation between Bragg wavelength and either strain or AE-RMS voltage can be obtained by rearranging data after the end of test, since the data sampling time of 4–5 s for OSA is slow compared to the sampling times of the others.

3. Results and discussions

3.1. Material properties of microcomposites

To obtain optimized testing conditions of microcomposites, two fibers and epoxy matrix and their IFSS between fiber and matrix are analyzed. Tensile strength of most ceramic fibers is highly dependent upon the gauge length of the specimen for the single-fiber tensile test due to the increasing probability of flaws along the fiber surface as the gauge length increases. SiC fiber is well known to be somewhat brittle and so can be easily weakened in tensile strength by the surface flaws. Table 2 shows the variation of tensile strength and elongation for two gauge lengths of 13.6 and 137 μm diameter SiC fibers, respectively. It is noticeable that the average tensile strengths for both fibers were widely distributed due to the existence of internal or external flaws and the heterogeneity between neighboring fibers. The shorter the gauge length is selected, the higher value for tensile strength and elongation are obtained. If a bimodal analysis can be used on the behalf of unimodal distribution, the fiber distribution may show a bimodality at a certain gauge length due to different type of flaws.

Table 3 shows the statistical distribution parameters for the single 13.6 μm SiC fiber. For statistical analysis, normal, lognormal, and Weibull distributions are applied. Fig. 4 shows Weibull distribution for the 13.6 μm SiC fiber strength at various gauge lengths. With the increase of the gauge length the tensile strength distribution decreases due to the increased surface flaw densities. Table 4 shows the correlation between the Bragg wavelength and either strain or AE-RMS voltage. Table 5 shows aspect ratio, Weibull parameters and IFSS for 13.6 μm SiC fiber/epoxy composites. By substituting the average fiber strength and the critical fragment length into Kelly–Tyson (4) and Drzal (5) equations, the IFSS and the modified IFSS using Weibull distribution are calculated.
Two IFSS values evaluated by two methods are similar to each other. Fig. 6 shows photographs of fractured SiC fiber/epoxy composite after tensile testing (a) without and (b) with a polarized-light. Although the fiber break does not clearly appear in Fig. 6(a), the breaking position is identified well and stress whitening around fiber breaking position appears clearly in Fig. 6(b). All three fibers consisting of two thin and thick SiC fibers and a fiber-optic were observed to be broken after testing.

3.2. Comparison of outcome by FBG and AE-PZT sensors

Two types of fiber-optic sensors are applied independently. Fig. 7 shows the wavelength shift versus the elapsed testing time for the first microcomposite embedded with a 3M fiber-optic sensor, whereas Fig. 8 shows a typical waveform induced by the breakage of 137 μm SiC fiber. Crosshead speed in the mini-tensile machine is controlled manually consistently to get almost constant strain rate. Any special or auxiliary device for controlling the strain rate was not used in the test. While the strain rate is controlled by the manual extension of the specimen with care through a simple test fixture (mini-tensile machine) with a gear mechanism of high reduction ratio in the linear movement. A strain gauge is used just to obtain the strain value of the specimen.

Sudden shift of wavelength exhibits by the break of 137 μm SiC fiber, and finally wavelength drops to zero due to the failure of fiber optic sensor in itself. Sudden drop of wavelength indicates that the fiber-optic sensor does not act any more as a sensor due to the disconnection of the fiber-optics sensor. Big shift of wavelength can be detected because of large plastic deformation due to the fracture energies induced by the break of the thick SiC fiber. On the other hand, the microfailure events from 13.6 μm SiC fiber cannot be detected in the wavelength plot. It means that the fiber fracture energies resulting from small diameter fiber breaks cannot be translated to the FBG sensor sensitively than as expected.

The second microcomposite using an Innovation fiber-optic sensor is tested further in detail combined with AE (Fig. 9). Crosshead speed in the mini-tensile machine is also controlled manually with care to obtain a consistent strain rate as the first microcomposite case. In Fig. 9, a solid line indicates strain change whereas a dotted line is AE-RMS voltage. It is observed that until the strain gauge is detached from the specimen surface at the strain of about 230 με, the strain increases roughly in a linear fashion. To this failure point, it takes about 255 s since the test started. A few peaks observed in AE-RMS voltage curve indicate that AE signals with very high energies are detected at these positions. A very big peak around 255 s may come from the adhesive failure of the strain gauge. Another two distinguished peaks before and after the failure of the strain gauge may occur from the 137 μm SiC fiber breaks.

The corresponding process measured by FBG sensor is shown in Fig. 10 where AE-RMS voltage and wavelength

### Table 4
Mechanical properties of the neat epoxy specimens using various curing agents

<table>
<thead>
<tr>
<th>Curing agent</th>
<th>No. of specimen (EA)</th>
<th>Tensile strength (MPa)</th>
<th>Modulus (GPa)</th>
<th>Strain at breakage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mPDA</td>
<td>4</td>
<td>84.2(7.0)</td>
<td>2.52(0.4)</td>
<td>5.5(0.8)</td>
</tr>
<tr>
<td>D400</td>
<td>6</td>
<td>41.4(3.8)</td>
<td>2.00(0.2)</td>
<td>8.8(2.6)</td>
</tr>
<tr>
<td>D400 + D2000</td>
<td>6</td>
<td>35.8(6.6)</td>
<td>1.76(0.2)</td>
<td>40.5(3.8)</td>
</tr>
<tr>
<td>D400 + D2000</td>
<td>6</td>
<td>24.6(1.9)</td>
<td>1.56(0.2)</td>
<td>66.6(5.2)</td>
</tr>
</tbody>
</table>

Values in parenthesis represent standard deviation.

* D400 = 3 g.
* D400:D2000 = 2.7 g: 0.3 g.
* D400:D2000 = 2.5 g: 0.5 g.

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The corresponding process measured by FBG sensor is shown in Fig. 10 where AE-RMS voltage and wavelength
for FBG sensor are shown as a solid line and a dotted line, respectively. Like the first microcomposite using a 3M fiber-optic sensor, it is observed that the FBG sensor output is also less insensitive for the fiber breakage of the 13.6 μm SiC fiber, due to the occurrence of the minor plastic deformation. It is also to the very large external disturbance such as an adhesive failure by strain gauge detachment.

It may be resulted from the different sensor characteristics or the sensitivity and failure locations, i.e. comparative distance from FBG sensor location. It is also notable that the identical microfailure phenomena are detected well via AE signals. It is considered that FBG sensor can be used together with AE sensor in order to monitor a different type of micro-deformation mechanism. This means that FBG sensor is basically effective in the case for evaluating micro-strain changes by the external disturbance around fixed certain point sensor. It may be unsuitable to detect the transient micro-deformation such as the elastic wave propagating through the solid as in AE.

Table 5
Weibull distribution parameters for the aspect ratio and IFSS of the 13.6 μm SiC fiber/epoxy composite

<table>
<thead>
<tr>
<th>Diameter (μm)</th>
<th>Aspect ratio (l_c/d)</th>
<th>Scale parameter (α)</th>
<th>Shape parameter (β)</th>
<th>IFSS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.6</td>
<td>49.7</td>
<td>97.8</td>
<td>3.6</td>
<td>26.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>23.5</td>
</tr>
</tbody>
</table>

a Weibull parameters for the aspect ratio.

b Drzal equation: \( \tau = (\sigma l/(2a))^\frac{1}{1-1/\beta} \).

c Kelly–Tyson equation: \( \tau = (\sigma l)/(2l_c) \).

Fig. 6. Optical micrographs of the fractured dual fiber composites containing three embedded fibers: (a) without and (b) with polarized-light.
To know the active range of a FBG sensor quantitatively, Bragg wavelength versus strain gauge output can be shown in Fig. 11. Measurable range using FBG sensor is about 450–1050 με in general (or the range of corresponding wavelength is about 1534.54–1535.26 nm for the sensor with Bragg wavelength of 1534 nm). Since this range is very narrow and limited than as expected, FBG sensor may not be suitable for the polymeric or metallic materials where plastic deformations accompany, but suitable for brittle materials or fatigue fracture where tiny deformations occur relatively. The slope of the very sensitive range is found as about $4 \times 10^{-3}$ nm/με.

3.3. Analysis of AE result

AE is basically a form of elastic wave emitting and propagating from or to the solid when a sudden change or disturbance of strain energy occurs inside solid. Especially, a sudden failure of fiber or matrix cracking may generate AE signal in the composite materials. Measurable signals for elastic wave transmission can be detected as electrical signal by PZT sensor attached on the surface of the microcomposite when microfailures such as fiber break and matrix cracking plus debonding at the interphase occur. Detected AE signals emanating from the specimen due to
tiny deformation or fracture occurring in the solid materials may be characterized precisely than any other method. Since the sensitivity of AE sensor to detect wavelength is about $10^{-12}$ m in maximum, it is very sensitive even to the tiny internal change of elastic wave intensity. However, it is notable that high sensitivity of sensor might increase the possibilities of accepting all kinds of noise considered to be undesirable, AE data should be analyzed more carefully rather than focusing on the measurement itself.

The results of the AE test for the second microcomposite using Innovative fiber-optic sensor can be summarized in Fig. 12. Fig. 12 shows (a) the cumulative of AE hits detected during 350 s from the beginning and to the end of the test, and (b) the signal amplitude with testing time. It is observed that the AE signal starts to occur at around 235 s and increases steeply up to 250 s, and then shows a transition of increasing slope. This slight change in strain curve can be observed in Fig. 9, however, it is hard to find the change after 255 s because of the adhesive failure of the strain gauge at the specimen.

Using a total of 688 AE signals in Fig. 12, Fig. 13 shows (a) signal amplitude versus duration time and (b) histogram of amplitude distribution. Bimodal distribution consists of two ranges, i.e. 37–55 and 55–67 dB, plus a few numbers of signals are distributed in 70–92 dB. Since AE data do not occur up to 235 s in Fig. 12, the range of 235–350 s has been analyzed intensively hereafter in Fig. 14. From Fig. 14(b), distinguishable aspect is that the range between 235 and 264 s and the range after 265 s are separated clearly. Hereafter the first range between 235 and 264 s is
defined as section ‘A’, whereas the second range between 265 and 345 s is also called as section ‘B’. The reason for discarding data after 345 s is that the impact wave occurring from the final catastrophic failure is considered as only noisy signal that may be unrelated to microfailure inside the composite.

Figs. 15 and 16 show AE signal analysis for two ranges in (a) amplitude versus duration and in (b) hit histogram by

![Fig. 11. Bragg wavelength as a function of longitudinal strain.](image1)

![Fig. 12. AE data acquired during the tensile testing using DFC specimens: (a) cumulative AE hits versus time; and (b) signal amplitude versus time.](image2)
amplitude as in Fig. 13. Signals having strong but a few numbers in the range of 70–97 dB and rather weak signal group in the range of 37–55 dB, which may come from fiber breakage plus the interfacial debonding, are occurring in the section A. On the other hand, most of the middle range signals in the range of 50–67 dB occur in the section B, which may come from matrix cracking mostly. This means that there is no signal in the range of 70–97 dB and two SiC fibers are found to be broken completely in the section A. There is also distinguishable difference in duration time in two sections, A and B. There are diverse distributions of signals from a few µs to 700 µs in the section A, whereas there are also most signals with very short duration time less than within 100 µs in the section B.

Two signals having 95 and 83 dB amplitudes and occurring in section A have been especially investigated. It is sure that the three signals may be coming from the breaks of 137 and 13.6 µm SiC fibers since their signal amplitude and energy are quite different from each other. Average fragment lengths of two fibers are about 2.7 and 0.67 mm, respectively. Noticing that the gauge length is only 25.4 mm, it is consistent with the observation that 137 µm SiC fiber is broken into only at 2 points whereas 13.6 µm SiC fiber is broken into at 32 points via polarized-light microscope.

3.4. Concluding remarks on two sensors related to microfailure detection

FBG sensor is unaffected by the electromagnetic or environmental field and having good compatibility with constituent materials of composites. With these advantages and capability of being embedded in the composite directly, it is expected to identify microfailure mechanisms of composites as a suitable sensor. However, FBG sensor proves to have lower sensitivity than AE-PZT sensor and its data sampling speed is slow. Due to this disadvantage, FBG sensor can be used for the limited and special applications, such as for the fatigue related to health monitoring of the structure having relatively small deformations for brittle materials, and especially for cure monitoring in polymeric composites.

In principle, the FBG can measure the strain at only one single point. Whether it can detect a fiber break in a SFC specimen depends on its proximity to the failure location. Moreover, in a real composite, when a few fibers break, the load can be transferred to other reinforcing fibers. In this case, even if a breakage occurs close to an embedded fiber-optic, it may be doubtful if the fiber-optic can pick up the fiber breakage. The use of FBG to monitor the microfailure can hence be considered...
Fig. 14. AE data acquired during 200–350 s by the tensile test: (a) cumulative AE hits versus time; and (b) signal amplitude versus time.

Fig. 15. Distribution analysis of AE signals acquired from 0 to 263 s period of Fig. 14: (a) a cross-plot of amplitude versus duration; and (b) AE hits versus amplitude.
not much to be useful practically. In addition, it is so obvious that the measurement of strain at one single point may not provide enough information to describe the whole failure process that involves the formation of multiple cracks.

One of notable limitations of FBG sensors related with the current test is relatively longer sampling time (order of 1 s or less) of OSA (Model Q8381A, Advantest Co.) (compared to AE sensor technique) for capturing the signal changes induced by the sudden breakage of the fibers in the specimen. The use of state of the art OSA, which can give much shorter sampling time than the OSA Q8381A might reduce the current limitation of FBG sensor during the test.

Although commonly used AE-PZT sensor is known to have high sensitivity for microfailure sources, there are some limitation in the application of AE-PZT for detecting undesired signals like many kinds of noises being very difficult to analyze quantitatively. It may need to know the nature of the damage as well as the location of each event using multiple AE detectors, so that whole damage process can be traced. Moreover, by analyzing the phase of signals, the nature of the event (whether it is an opening crack, as for a breaking fiber, or a sliding crack, as in interfacial failure) can be determined. To quantify the signals correlated with

the microfailure process or source of AE occurrence, even the precise change of frequency (or power) spectrum should be studied further via fast Fourier transfer. Since there are too many experimental factors affecting the frequency spectra, clear and quantitative information should be obtained from the well-controlled raw data.

4. Conclusions

Nondestructive evaluation of microfailure mechanisms in two SiC fiber/epoxy composites is investigated using a directly embedded fiber-optic sensor attached with an AE-PZT sensor simultaneously. In order to compare two sensors quantitatively rather qualitatively, IFSS is obtained by optimized fragmentation testing condition, and optical observation of microfailure phenomena inside micro-composite is contributed. FBG sensor exhibits sudden wavelength shift due to plastic deformation by larger diameter SiC fiber breakage, whereas AE-PZT monitors much more precise microfailure process. Since FBG sensor can measure the strain at only one single point, the detection of a fiber break in SFC specimen depends on its proximity to the failure location. Moreover, micro-strain measurement at one single point may not provide sufficient information on the total
microfailure process including multiple fiber breakage and matrix crack. AE-PZT sensor can be effective in detecting the microfailure by elastic wave propagation through the composite materials, whereas FBG sensor can be more effective in measuring the continuous micro-strain change due to the internal disturbance such as resin curing monitoring.

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References