Comparison of Nondestructive Damage Sensitivity of Single Fiber/Epoxy Composites Using Ceramic PZT and Polymeric PVDF Sensors By Micromechanical Technique and Acoustic Emission

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Micromechanical 시험법과 AE를 이용한 세라믹 PZT 및 고분자 PVDF 센서에 따른 단섬유 강화 에폭시 복합재료의 비파괴 손상감지능 비교

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KEY WORDS: nondestructive evaluation (NDE), damage sensing, polyvinylidene fluoride (PVDF), lead-zirconate-titanate (PZT), micromechanical technique, acoustic emission (AE)

ABSTRACT

Conventional piezoelectric lead-zirconate-titanate (PZT) senor has high sensitivity, but it is very brittle. Recently polymer films such as polyvinylidene fluoride (PVDF) and poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) copolymer have been used as a sensor. The advantages of polymer sensor are the flexibility and mechanical toughness. Simple process and possible several shapes are also additional advantages. Polymer sensor can be directly embedded in a structure. In this study, nondestructive damage sensitivity of single basalt fiber/epoxy composites was investigated with sensor type and thermal damage using AE and oscilloscope. And AE waveform for epoxy matrix with various damage types was compared to each other. The damage sensitivity of two polymer sensors was rather lower than that of PZT sensor. The damage sensitivity of PVDF sensor did not decrease until thermal damage temperature at 80°C and they decreased significantly at 110°C. However, the damage sensitivity of P(VDF-TrFE) sensor at 110°C was almost same in no damage sensor. For both top and side impacts, the difference in arrival time increased with increasing internal and surface damage density of epoxy matrix.

Nomenclature

Δt : Difference in arrival time
V : Wave velocity
D : Distance between two sensors
d : Source location

1. INTRODUCTION

Piezoelectric lead-zirconate-titanate (PZT) as a sensor has an excellent sensitivity and a wide application of the structure materials, whereas PZT is brittle due to ceramic nature [1]. Recently, polymer film such as polyvinylidene fluoride (PVDF) and poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) copolymer have come into increasing use as a sensor [2,3]. PVDF is a semicrystalline polymer with an approximate degree of 50% crystallinity. Like other semicrystalline polymers, PVDF consists of a lamellar structure mixed with amorphous region. *Piezo* film is a flexible, lightweight, tough engineering plastic available in a wide variety of thickness and large contacting area. Simple process and possible several shapes are additional advantages. Polymeric sensor can be directly attached or embedded

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to structure materials without disturbing its mechanical motion.

AE is well known as one of the important nondestructive evaluation (NDE) methods. The elastic wave can be detected and monitored by sensors to provide information about AE source location and AE source characteristics, which in turn can aid structural damage assessment [4,5]. A very useful method for evaluation AE has been to correlate AE signal energy with AE source physical process that essentially is rapid release of elastic energy, such as fracture. The AE can monitor the fracture behavior of composite materials, and can characterize many AE parameters to understand the type of microfailure sources during the fracture progressing. When tensile loading is applied to a composite, AE signal may occur from fiber fracture, matrix cracking, and debonding at the fiber-matrix interface [6-8].

In this study, nondestructive damage sensitivity of basalt fiber/epoxy composites was investigated with sensor type and thermal damage using AE. And AE waveform for epoxy matrix with various damage types was compared to each other.

2. EXPERIMENTAL

2. 1. Materials

Basalt fiber was used as a reinforcing material. Tensile strength and Young's modulus of basalt fiber were 2-4 GPa and 85 GPa respectively. The average diameter of the basalt fiber was about 97 μm. Two types of PVDF and P(VDF-TrFE) copolymer films (Measurement Specialties Inc.) were used as piezo-electric polymer sensor. Semicrystalline PVDF and P(VDF-TrFE) copolymer exhibit the highest ferroelectric polarization and electromechanical responses among the known polymers. Thermal stability and valuable service temperature range are known to be higher for P(VDF-TrFE) copolymer. Used epoxy resin (Kukdo Chemical Co. YD-128, Korea) is based on diglycidyl ether of bisphenol-A (DGEBA). Two types of polyoxypropylene diamene (Jeffamine D400 and D2000, Huntzman Pertochemical Co.) were used as curing agents. Flexibility of specimens was controlled by the relative proportions of D400 *versus* D2000.

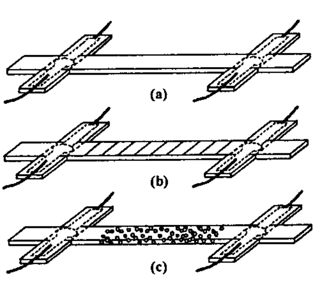

Fig. 1. Schematic figure of epoxy matrix with various damage types for (a) no damage, (b) surface damage and (c) air bubble

2. 2. Methodologies

2.2.1. Preparation of Damage Testing Specimens

Figure 1 shows a testing specimen to evaluate arrival time and wave velocity as a function of various damage conditions for (a) damage, (b) surface damage and (c) internal air bubble. Surface damage and internal air bubble was induced by control of damage density and angle. PVDF and P(VDF-TrFE) sensors were embedded in both end sides of the specimen and PZT sensor was attached on the surface of the specimen.

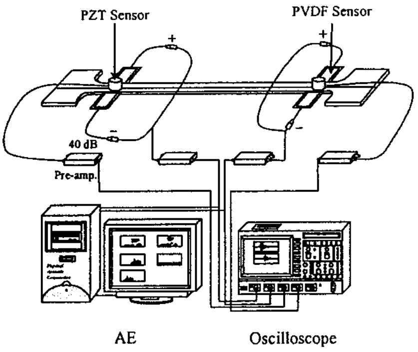

Fig. 2. Schematic figure for source location by AE and Oscilloscope

2.2.2. Source Location and Damage Sensing

AE source location of fiber fracture for basalt fiber/epoxy composites was performed by two PZT and two polymeric sensors. Figure 2 shows schematic figure for source location by AE and oscilloscope. The wave velocity was calculated by measurement of the difference in arrival time, Δt. Δt is given as

$$\Delta t = \frac{D}{V} \tag{1}$$

where D is the distance between two sensors, V is propagation velocity of a regular wave and Δt is arriving time difference. The critical location, d is given as

$$d = \frac{1}{2}(D - \Delta t \cdot V) \tag{2}$$

where d is distance according to the first arriving sensor

AE signals were detected using a miniature PZT sensor (Resonance type, PICO by PAC) PVDF and P(VDF-TrFE) sensors. PZT sensor has the peak sensitivity of 54 Ref V(m/s) and resonant frequency at 500 kHz. The outputs of two sensors were amplified by 40 dB at preamplifier gain. The threshold levels were set up as 30 dB for PZT sensor and as 40 dB for PVDF sensor, respectively. The threshold level was rather higher than that of PZT sensor because of the noise of PVDF sensor. The signal was fed into an AE signal process unit (MISTRAS 2001), where AE parameters were analyzed using in-built software. The typical AE parameters such as hit rate, peak amplitude, and event duration were investigated for the time and the distribution analysis.

3. RESULTS AND DISCUSSION

3. 1. Source Location with Thermal Damage

Figure 3 shows waveforms for fiber fracture signal of basalt fiber/epoxy composites with fracture location by (a) AE and (b) oscilloscope. The difference in arrival time for source location could be calculated by waveform analysis using AE and oscilloscope. The difference in arrival time by oscilloscope can be measured more accurately compared to AE because in case of AE the difference in arrival time can be measured using event over threshold level, whereas in case of oscilloscope it can be measured directly using the first event.

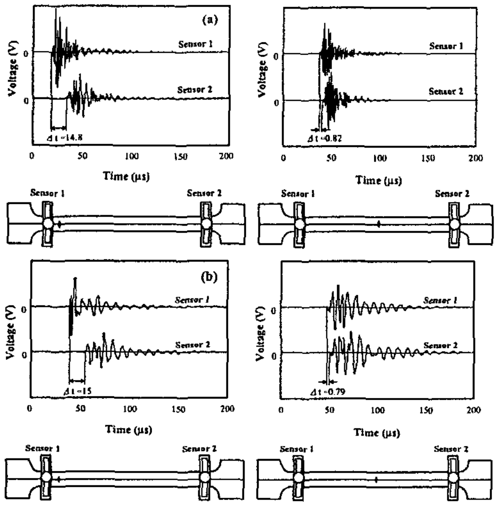

Fig. 3 Waveforms for fiber fracture signal with location by (a) AE and (b) oscilloscope

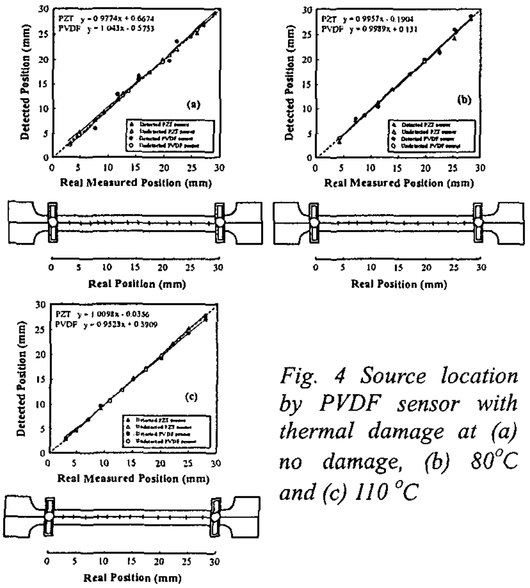

Fig. 4 Source location by PVDF sensor with thermal damage at (a) no damage, (b) 80°C and (c) 110 °C

Figure 4 shows source location for basalt fiber/epoxy composites by PVDF sensor with thermal damage at (a) no damage, (b) 80°C and (c) 110°C. The damage sensitivity of PVDF sensor was rather lower than that of PZT sensor. The damage sensitivity of PVDF sensor did not decrease until thermal damage temperature at 80°C. However, the sensitivity decreased significantly at 110°C. Figure 5 shows the source location for basalt fiber/epoxy composites by P(VDF-TrFE) sensor with thermal damage at (a) no damage and (b) 110°C. The damage sensitivity of P(VDF-TrFE) sensor was maintained until thermal damage temperature at 110°C.

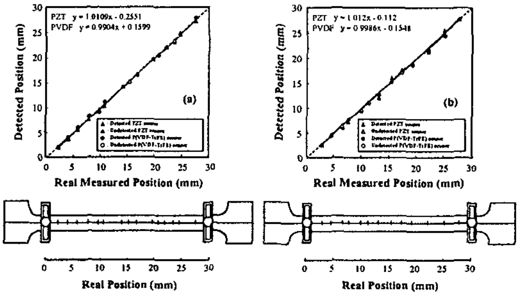

Fig. 5 Source location by P(VDF-TrFE) sensor with thermal damage at (a) no damage, (b) 110°C

Figures 6 and 7 show the AE waveforms and their fast Fourier transform (FFT) for basalt fiber fracture and matrix crack detected by (a) PVDF, (b) P(VDF-TrFE) copolymer and (c) PZT sensors. In the all sensors, fiber and matrix signals were detected. For both fiber fracture and matrix crack signals, the voltage of waveform and frequency detected by PZT sensor were higher than those of polymeric sensors. It may be because basalt fiber is more brittle than epoxy matrix. The voltage of fiber fracture was much higher compared to matrix crack signal. The wave voltage and their FFT result of fiber fracture measured by PVDF sensor was almost same in P(VDF-TrFE) sensor.

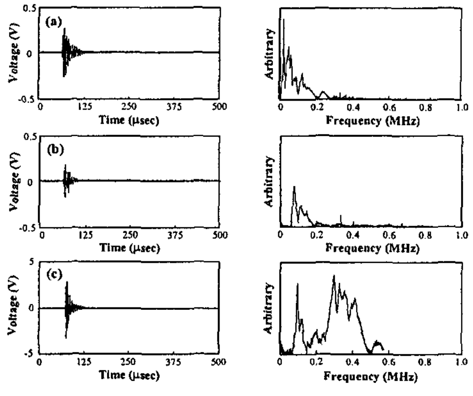

Fig. 6 Waveforms and their FFT analysis of fiber fracture signal: (a) PVDF, (b) P(VDF-TrFE) and (c) PZT sensors

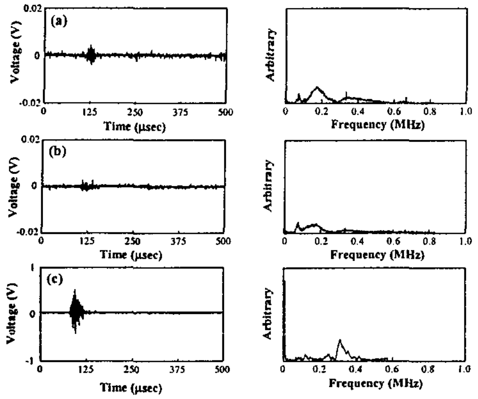

Fig. 7 Waveforms and their FFT analysis of matrix crack signal: (a) PVDF, (b) P(VDF-TrFE) and (c) PZT sensors

Table 1 Comparison of arrival time for epoxy matrix with various damage types

Damage Type and Size	Arrival Time, Δt (μs)		Wave Velocity [2] (m/sec.)
	Top Impact	Side Impact	
No Damage	55.2 (0.21) [1]	54.4 (0.20)	1812
Damage 20 mm	56.5 (0.12)	55.7 (0.12)	1770
Damage 10 mm	58.7 (0.18)	58.2 (0.28)	1704
Damage 5 mm	61.1 (0.19)	60.2 (0.25)	1637
Air Bubble 30 mm	57.7 (0.11)	56.2 (0.18)	1733
Air Bubble 60 mm	61.2 (0.10)	60.3 (0.16)	1634
Longitudinal 2 Line	56.2 (0.18)	54.7 (0.11)	1779
Longitudinal 4 Line	57.1 (0.12)	56.9 (0.11)	1751
45° Damage 20mm	56.3 (0.20)	55.4 (0.16)	1776
45° Damage 10mm	57.6 (0.19)	56.7 (0.19)	1736
45° Damage 5mm	60.4 (0.17)	59.8 (0.16)	1656

1) Standard deviation
2) For top impact

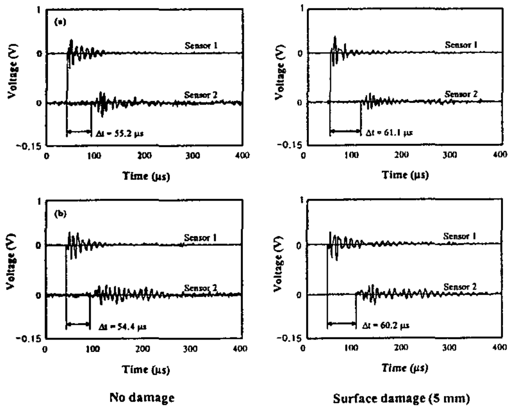

Fig. 8 Waveforms of epoxy matrix with surface damage density for (a) top and (b) side impacts

3.2. Waveform Analysis for Epoxy Matrix with Damage Types

Table 1 shows the difference in arrival time and wave velocity for epoxy matrix with various damage types. The difference in arrival time was calculated by oscilloscope using pencil-lead-break method. For both top and side impacts, the difference in arrival time increased with increasing damage density. Arrival time for side impact was faster than that of top impact because for top impact extensional wave appeared more dominant compared to the flexural wave. The result of wave velocity was consistent with the trend of the difference in arrival time.

Figure 8 shows waveform of epoxy matrix with damage and impact conditions by PVDF sensor. In the specimen with surface damage, AE amplitude of waveform was smaller compared to no damage case. For side impact, an extensional wave has lower voltage and faster arrival time compared to top impact case.

4. CONCLUSIONS

Nondestructive damage sensitivity of single basalt fiber/epoxy composites was investigated with sensor type and thermal damage using AE. The difference in arrival time and wave velocities of epoxy matrix with internal air bubble and external surface damage were compared to no damage specimen. The damage sensitivity of two polymer sensors for fiber fracture was rather lower compared to PZT sensor. The damage sensitivity of PVDF sensor did not decrease until thermal damage temperature at 80°C, whereas for P(VDF-TrFE) sensor was almost same in no damage sensor until reaching at 110°C. For both fiber fracture and matrix crack signals, the voltage of waveform and frequency detected by PZT sensor were higher than those of polymer sensors. The wave voltage and FFT result of fiber fracture measured by PVDF sensor was almost same in P(VDF-TrFE) sensor. For both top and side impacts, the difference in arrival time increased with increasing damage density of epoxy matrix.

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