BENDING FRACTURE BEHAVIOR OF 3D-WOVEN SiC/SiC COMPOSITES WITH TRANSPERSION COOLING STRUCTURE CHARACTERIZED BY AE WAVELET ANALYSIS

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Abstract

The fracture behavior of the SiC/SiC composites was examined by 4-point bending tests. The AE signals detected during the tests were processed by AE wavelet analysis, which extracted the first and second major frequencies from continuous wavelet transform (CWT) diagram. Consequently, the two-frequency combination analysis can detect local frequency component and characterize a wavelet diagram well. A history of these major frequencies was correlated to initiation and propagation of typical crack paths, such as cracks in SiC matrix and crack propagation along thickness. Although other micro-damages, such as fiber breaks and sliding/debonding at interfaces between fiber and matrix, have not been correlated to the AE signals, the results suggest that the two-frequency combination analysis based on CWT has great potential to characterize the micro-damages of the composites.

Introduction

SiC/SiC composites have been studied in order to increase the temperature capability of jet engine component [1, 2]. An increase in the temperature capability would raise the gas temperature and reduce the need of air cooling, both of which would improve the efficiency of a jet engine. However, active cooling is still needed for the composites to preserve structural strength, since the temperature capability of the composites is lower than the gas temperature (e.g. 1600°C at turbine inlet). In order to develop a simple cooling structure with high efficiency, a transpiration-cooling structure was created in the composites by decreasing a volume fraction of SiC matrix, which was fabricated by four cycles of matrix densification process, “polymer impregnation and pyrolysis (PIP)” [3]. In order to investigate the PIP-cycle effect on the fracture mechanism, flexural loading and unloading test was carried out in a previous study [4]. However, the observed fracture behavior could not be correlated to the captured AE signals by examining AE parameters, such as amplitude and energy. In order to fully understand the bending fracture behavior and monitor micro-damage evolution under long-term evaluation (e.g., thermal cycling test, fatigue test), better correlations between captured AE signals and micro-damages are needed.

Many authors have studied frequency analysis based on frequency domain (FT) or time-frequency domain (WT) in order to investigate correlations between micro-damages and AE signals [5-9]. Many publications on the frequency analysis dealt with CFRP or GFRP, both of which were fabricated by materials of quite different properties. As the SiC/SiC composites are fabricated by materials with similar properties (e.g., chemical compositions and mechanical property), the frequency analysis with a capability to detect minor differences in AE waveforms is required. In recent studies, the discrete wavelet transform (DWT) has often been applied to characterize the AE waveform. The DWT decomposes a signal to several scale levels that correspond to frequency range. However, it appears that the scale level of the DWT may give only a rough estimation for characterizing the AE waveforms emitted from the SiC/SiC composites. Thus, this study applied the continuous wavelet transform (CWT), which can analyze frequency at a finer scale, for the analysis of the AE waveforms of the composites.

The purpose of this study is to correlate the micro-damages of the SiC/SiC composites to the AE waveforms by analyzing the first and second major frequencies utilizing the continuous wavelet transform (CWT).
Materials and Experimental Procedures

Materials and specimens

The SiC/SiC composites used in this study were made of Tyranno™ ZMI SiC (Si-C-O-Zr) fiber of Ube Industries, Ltd. and SiC matrix. The composites have the 3D-orthogonally woven structure as schematically shown in Fig. 1. The 3D-woven architecture consists of three layers of X bundles, four layers of Y bundles and Z bundles. Figure 2 shows a cross-sectional view of YZ plane along “aa”. The material composition near surface is also depicted in the figure. Tensile side is not flat because of the woven structure, which will result the notch-like geometry resulting in stress concentration. The location of the notch-like geometry indicated by a gray arrow is called a “corner” in this paper.

First, a carbon interface layer derived from the chemical vapor infiltration (CVI) process was coated on the fibers, then the SiC matrix was infiltrated using methyl-trichlorosilane by a CVI process and from polycarbosilane by several cycles of PIP process. The porosity was controlled by varying the number of PIP cycles. The specimens fabricated with 2, 4 and 9 cycles of PIP are called P2, P4 and P9. It is important that P2 and P4 have transpiration-cooling structures.

After the PIP treatments, the specimens were cut and coated with a thin layer of CVI-SiC. Detailed volume fractions of the specimens are given in Table 1. The dimensions of the specimen were 50 mm length x 4 mm (approx.) width x 2 mm (approx.) thickness. The width corresponds to the size of two pitches of the textures.

![Fig. 1. Schematic diagram of SiC/SiC weave (Fiber volume ratio; X:Y:Z=1:1:0.2, pitch=2 mm).](image)

![Fig. 2. Composite cross section along “aa” in Fig. 1.](image)

Table 1. Volume fraction of fiber, matrix and porosity.

<table>
<thead>
<tr>
<th>Type</th>
<th>Fiber / %</th>
<th>Matrix / %</th>
<th>Porosity / %</th>
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<tbody>
<tr>
<td>P2</td>
<td>41</td>
<td>29</td>
<td>30</td>
</tr>
<tr>
<td>P4</td>
<td>41</td>
<td>34</td>
<td>25</td>
</tr>
<tr>
<td>P9</td>
<td>41</td>
<td>46</td>
<td>13</td>
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Experimental Procedure

Four-point bending tests were carried out with inner span of 10 mm and outer span of 30 mm at room temperature in air. Loading was applied by a universal testing machine (Instron, 5505) along Z-direction under a constant crosshead speed of 0.5 mm/min so that the tensile stress was applied along X-direction. Deformation of the sample was measured parallel to the Z-axis by the displacement transducer and recorded by a PC-based data recorder (Kyowa, UCAM-500A).

During the test, AE signals were monitored by two wide-band AE sensors (Fuji Ceramics, M5W), which were attached on both ends of the sample. The AE signals were amplified 20 dB and the threshold level was set to the value of 3.16 mV at the input of the amplifiers. The AE signals were processed by an AE analyzer (PAC, PCI-2 AE system) with AEWin™ operating software. Recorded AE waveforms were post-processed by the CWT. Morlet function was chosen as the mother wavelet with non-dimensional frequency $\omega = 8$ [10].
Results and Discussion

The first and second major frequencies in CWT diagram

AE waveforms acquired in this study showed characteristic CWT diagrams in the time-frequency domain. As an example, some characteristic CWT diagrams obtained from specimen P9 are shown in Fig. 3. Each diagram has two or more characteristic peak frequencies except for Fig. 3(a), which has only one peak frequency near 0.3 MHz. The sensor used has a slightly higher response between 0.2 and 0.3 MHz and flat frequency response beyond 0.5 MHz. Thus, a frequency near 0.3 MHz is detected as the dominant frequency in most of the diagrams. Second characteristic peak frequency of the CWD diagrams often appears below or above the dominant frequency of ~0.3 MHz. It appears that a combination of several peak frequencies can possibly characterize and classify the CWT diagram. In this study, the 1st and 2nd major frequencies were utilized for this attempt.

Figure 4 shows the CWT diagram of an AE waveform, including cross-sectional views taken along “aa” and “bb” on the CWT diagram. In the CWT diagram, a pair of the frequencies “FRQ1” and “FRQ2” (white arrows) are the two characteristic frequencies of this WT coefficient contour. The cross-sectional view along line “aa” is a time history of WT coefficient at the frequency “FRQ1”. Ni and Iwamoto [9] proposed that a WT-time curve at a specified frequency on FFT plot can identify the occurrence time and duration of the micro-fracture mode of single carbon-fiber composites. The WT-frequency curve taken from “bb” line of the CWT diagram exhibits a distribution of WT coefficient indicating “FRQ1” to be the major frequency. This curve does show that the frequency peak is also located near “FRQ2”, but it fails to properly account for the intensity at “FRQ2”, even though this is shown clearly in the CWT diagram. Thus, either WT-time or WT-frequency curve cannot fully characterize the CWT diagram.

Figure 5(a) shows a CWT diagram projected into WT-frequency plots, while Fig. 5(b) shows the FFT diagram of the same AE waveform for a comparison. The projected WT-frequency curves lost time information, but the frequency and intensity information of two major peaks are preserved. Figure 5(b) shows that the first major frequency in the projected WT-frequency curve
Fig. 4. Wavelet diagram with cross sectional views, taken along lines “aa” and “bb”.

Fig. 5. The major and second major frequencies in projected WT-frequency curve (WT-frequency curve not time-averaged.) (a) Projected WT-frequency curve, (b) FFT spectrum.

is recognized only as a secondary frequency in the FFT envelope due to the time averaging effect. Thus, FFT analysis fails to detect important frequency information. FFT results also indicate the highest peak at 0.25 MHz, close to the resonance frequency of the AE sensor. This can easily be mistaken as a characteristic major frequency of the AE waveform and implies that FFT-based methods must be used with caution.

**AE wavelet analysis**

Figures 6(a) and (b) show histories of the first and second major frequencies, respectively, of the first hit AE signals obtained during the bending test of P4 (Due to space limitation, the data
of P2 and P9 are not shown). Relative values of the WT coefficients of the major frequency components are shown by the circle diameter. In Fig. 6(a), the 1st major frequency components are distributed in a limited frequency band of 250 to 500 kHz. This range corresponds to the high sensitivity range of the AE sensor-specimen combination, identified by the through-transmission experiment using a pair of M5W sensors with tone-bursts. The 2nd major frequencies, shown in Fig. 6(b), are more widely distributed and frequency components over 500 kHz and below 250 kHz were also observed.

![Fig. 6. Frequencies in CWT diagrams. (a) The 1st major frequency. (b) The 2nd major frequency.](image)

The 1st and 2nd major frequency components are shown together in Fig. 7 with connecting link between the two frequencies, since a combination of the two major frequencies can be considered to represent a contour pattern shown in Fig. 3. A caption above the figure described the bending fracture process, which had been observed in the loading/unloading test [4]. The corner crack was generated in the CVI-SiC and PIP-SiC matrices on the tension-side surface, which
grew along thickness direction and resulted in the bending fracture. The PIP-SiC crack was observed in the matrix-rich region near cavity and on compressive-side surface [4]. The two-frequency components of low WT coefficient with widely distributed frequency range in 50-1050 kHz were observed throughout the test. The signature of the AE signal can be considered to correlate with the initiation and propagation of the crack in the both CVI-SiC and PIP-SiC matrices, since the AE signals with the signature in the stress range of 50 - 100 MPa corresponded to those micro-damages.

In the stress range above 140 MPa, the AE signals with relatively large WT coefficient were detected. These signals correlated with the micro-damages due to the corner-crack propagation along thickness. The micro-damages are considered to be fiber-breakage, sliding and debonding at interface. The frequency component near 800 kHz with large WT coefficient may correlate to the breakages of the load-bearing SiC fiber in the lower X-fiber bundle. In the figure, it is noteworthy that the large deflection of the stress-displacement curve as indicated by the black arrow in Fig. 7 was accompanied with low-frequency component. This indicated that the low-frequency component also carried useful information to explain the fracture behavior of the SiC/SiC composites.

The two-frequency combination with large WT in Fig. 7 appears to have some patterns, which can be classified to some groups. Therefore, the pattern recognition of the combination may lead to correlate the AE signals to micro-damages, such as SiC-fiber breakage, interfacial sliding and debonding. Further study will be carried out to find the correlation by the two-frequency combination analysis extracted from CWT.

Conclusions

The wavelet analysis of AE signals based on the two-frequency combination extracted from CWT diagram was applied to investigate the correlation between AE signals and micro-damages in the SiC/SiC composites with transpiration structure and following conclusions were obtained.

1) Two-frequency combination analysis can detect frequency components that characterize the contour pattern of the CWT diagram.
2) The AE signal with low WT coefficient with widely distributed frequency corresponds to the crack in the CVI- and PIP-SiC matrices.
3) The AE signal detected during crack propagation along thickness have a potential to be classified to groups by recognizing patterns of two-frequency combination, which may correlate the AE signal to micro-damages such as fiber breakage, sliding and debonding between fiber and matrix.

References