Compression damage identification of stitched 2D-C/SiC based on acoustic emission pattern recognition

Yongzhen Zhang, Xiaoyan Tong, Peng Lyu, Zhiyong Tan, Leijiang Yao, and Bin Li

ABSTRACT

Compression tests of stitched 2D-C/SiC at room temperature were implemented and monitored by acoustic emission (AE). The t-Distributed Stochastic Neighbor Embedding (t-SNE) and the ward-link hierarchical clustering (WLHC) algorithm were used to perform the pattern recognition of the AE data. AE signals were divided into four clusters and labeled by matrix cracking in fiber bundle, matrix cracking between fiber bundles, fiber cluster breakage, interlaminar delamination & friction respectively, according to their physical foundation. It is found: (1) the compression failure process of stitched C/SiC experiences the initial damage stage with a few low-energy AE signals, the damage development stage beginning with high-energy fiber cluster breakage, and the damage acceleration stage in which fiber cluster breakage and interlaminar damage develop rapidly; (2) the macroscopic fracture generally originates from the sparse location of the stitches, and the spacing and uniformity of the stitches have a great impact on the form of fiber breakage and the area of individual delamination damage rather than the direction of the stitches; (3) fiber cluster breakage and interlaminar delamination & friction are the main factors of stitched 2D-C/SiC compressive failure modes, the sum of the corresponding AE events accounts for about 60% of all AE events.

1. Introduction

Carbon fiber toughened silicon carbide composite (C/SiC) has become one of the key materials for reusable thermal protection structures of aerospace vehicles and ultra-high sound speed aircraft due to its light weight, high specific strength, high specific modulus, good thermal mechanical properties and impact resistance [1–5]. Chemical vapor infiltration (CVI), polymer impregnation process (PIP), and liquid silicon infiltration (LSI) are generally used for the fabrication of C/SiC. Compared with CVI and LSI, PIP has many advantages such as lower component fabrication time to reduce costs significantly and lower fabrication temperature [6,7]. Compression is an important load state of C/SiC materials in service [8,9]. Moreover, the C/SiC components will fail due to the compression damage even when the components are loaded in tension [10]. Therefore, the mechanical properties and damage evolution of C/SiC prepared by PIP under compression load are of great importance and should be taken account for material designs.

In recent years, researchers have conducted many investigations on its mechanical properties of C/SiC composites. They often rely on physical information released from the internal changes in materials to describe the damage process, such as electrical resistance, mechanical parameters, acoustic emission (AE) [11–17]. AE is defined as a phenomenon whereby transient elastic waves are generated by the rapid release of energy from a localized source or sources within a material [18]. AE provides the feasibility to continuously monitor the material under loading and has become one of the most sought Nondestructive Evaluation (NDE) techniques in structural health monitoring over the past few decades [19–22]. However, there are challenges in the application of AE in the study of damage mechanisms of ceramic matrix composites (CMCs). One of the most important is that the complexity of AE source itself, such as its complex propagation and attenuation processes within the material, which make it difficult to correlate AE events with microscopic damage mechanisms. Researchers have tried to solve this problem with pattern recognition technology, mainly unsupervised cluster analysis [23–25]. This method has been used to analyze several kinds of CMCs and identifies that AE signals grouping has a strong correlation with damage mechanisms [13,14,25–27].

The aim of this research is to study the compressive failure mechanism by using advanced pattern recognition methods with AE data obtained from stitched 2D-C/SiC composites compression tests. The t-Distributed

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Stochastic Neighbor Embedding (t-SNE) as a nonlinear dimension reduction method is used instead of common principal component analysis (PCA) to help realize the recognition of natural clusters of high-dimensional AE data. Combined with the AE data and observation of fracture surfaces, various damage modes and their evolution were identified by the AE pattern recognition method proposed in present paper.

2. Methodology of AE pattern recognition

There are two types of pattern recognition: supervised pattern recognition with known label data and unsupervised pattern recognition without known label data; AE signals generated by different microscopic fracture mechanisms have their special features, which can be described by some features extracted from the AE waveforms, such as energy, amplitude, rise time, etc. Since no labeled data is available, an unsupervised methodology is used to perform the pattern recognition. The methodology proposed for the AE pattern recognition is schematically represented in Figure 1.

Firstly, the compression tests and AE on-line monitoring of C/SiC composites were carried out to collect the mechanical properties and AE data. Since each AE signal is composed of many AE features, the AE data must be fully preprocessed to build a data set suitable for the clustering task. The complete link hierarchical clustering algorithm (CLCA) was used to select uncorrelated AE features. To facilitate the visualization of spatial relationship of AE data, the t-SNE was used as a non-linear technique to dimensionality reduction, which creates a group of low-dimensional points from high-dimensional data [28]. Natural clusters in high-dimensional data can be found through low-dimensional points. The idea is to embed high-dimensional points in low dimensions in a way that respects similarities between points. Nearby points in the high-dimensional space correspond to nearby embedded low-dimensional points, and distant points in high-dimensional space correspond to distant embedded low-dimensional points.

Secondly, the ward-link hierarchical clustering (WLHC) method was adopted to automatically cluster and separate the AE signals. WLHC clustering algorithm is to minimize the following objective function. With hierarchical clustering, the objective function starts out at zero (because every point is in its own cluster) and then grows as we merge clusters. Ward’s method keeps this growth as small as possible [28].

\[
\Delta(A, B) = \sum_{i \in A \cap B} ||x_i - m_{A,B}||^2 - \sum_{i \in A} ||x_i - m_A||^2 - \sum_{i \in B} ||x_i - m_B||^2 + \frac{n_A n_B}{n_A + n_B} ||m_A - m_B||^2
\]  

(1)

Where \( m_j \) is the center of cluster \( j \), and \( n_j \) is the number of points in it. \( \Delta \) is called the merging cost of combining the clusters A and B.

Calinski-Harabasz index (CH) [29], Davies-Bouldin (DB) index [30], and Silhouette(Silh) index [31] were selected to check the validity of the clustering result. The larger CH index and Silh index, and the smaller DB index, the better the clustering result. Finally, each cluster was correlated to its corresponding damage mechanism by damage modes understanding.

3. Experimental

3.1. Preparation of specimens

C/SiC composites were prepared by precursor infiltration and pyrolysis (PIP) process [32]. Ten layers of five harness satin weave (SHSW) carbon clothes (3 K T-300, Toray) were laminated and stitched by the same fibers. The fiber volume content is about 40%. The PCS/xylene solution prepared by polycarbisilane (PCS) and xylene was used as the impregnant. The pyrolysis is carried out at 1100°C, and the impregnation-pyrolysis process was repeated until the weight gain rate drops below 1%. The C/SiC was machined into straight strip samples that the length, width, and thickness are 154 mm, 18 mm, and 6.5 mm, respectively.

3.2. Compression tests and AE monitoring

The room temperature compression tests were performed on a servo-hydraulic test machine (Model INSTRON 8801) with displacement-controlled loading. Three samples were tested and denoted by S1, S2, S3, which are taken from the same stitched C/SiC plate. The Morphologies of the fractured specimens were observed with a scanning electron microscope (TESCAN, VEGA 3 LMU).
The AE signals generated during the tests were detected by a WD sensor (Physical Acoustic Corporation, PAC) attached to sample. AE data was collected during the compression tests using the PCI-2 AE system (PAC), with a sampling rate 2MSPS. AE signals were frequency filtered between 20 kHz and 1 MHz, pre-amplified by 40 dB. An amplitude threshold 40 dB was set to obtain AE hits.

4. Results and discussion

4.1. Results of compression tests

The crosshead displacement loading rate of compression tests is 0.5 mm/min, and the ultimate strength of three samples are listed in Table 1. The stress-displacement curves and the cumulative absolute energy (Ab-Energy) curves of the specimens are shown in Figure 2. The macroscopic fractures of the samples are shown in Figure 3. Under the same test conditions, the macroscopic fractures of the specimens are quite different, damages such as fiber shear fracture and delamination cracks appeared. However, the stress-displacement curves cannot explain the differences in the macroscopic fractures and the damage evolution mechanism of the specimens.

4.2. Unsupervised clustering of AE signals

Each AE signal collected from the compression tests of three samples was represented by a set of features. The AE acquisition system provides 12 features, i.e. Rise time (Rt), Counts (Ct), PAC Energy (P-Eng), Duration (Dur), Amplitude (Amp), Average frequency (Ave-F), Amplitude frequency (Amp-F), Reverberation frequency (R-F), Initiation frequency (I-F), Absolute energy (A-Energy), Frequency Centroid (F-C), and Peak frequency (P-F). To optimize the clustering procedure, a subset of uncorrelated features was pick up by CLCA using the correlation matrix of the 12 features. After the feature selection, the AE data was identified using t-SNE and WLHC cluster analysis. Figure 4 shows the CH index, DB index, and Silh index calculated by the clustering results of three specimens obtained by taking the number of clusters 2–10. It is found that the number of clusters c = 4 gives the best result. Thus, the AE signals can be divided into four classes. Table 2 summarizes the mean characteristics of the obtained clusters of AE signals.

4.3. Cluster labeling

In CMCS, material damage can be classified into several kinds of microscopic damage mechanisms. First, Matrix cracks initiate at the macro pores inside

| Sample No. | S1  | S2  | S3  | Average | Standard deviation |
|------------|-----|-----|-----|---------|--------------------|
| Strength/MPa | 168.7 | 167.3 | 185.4 | 173.8 | 10.07 |

Figure 2. Cumulative Ab-energy with crosshead displacement and time of specimens.
the composites and propagate through the inter-yarn matrix. Then, the cracks propagate inside the transverse yarns and the axial yarns. These cracks are deflected by the fiber–matrix interphase, leading to interface debonding. Some fibers (fiber clusters) are broken under local high stress. The fracture of the fibers promotes the acceleration of the crack propagation in the longitudinal direction. The interlaminar delamination and friction with a large damage area occur in a large amount, which lead to instable fracture of specimens under compression load. Micrographs of the fracture surfaces (Figure 5) shows some microscopic damage modes, such as fiber cluster breakage, matrix cracking between fiber bundles. Interlaminar delamination can also be observed in Figure 3. The AE signals collected were generated by these damage modes. It is reasonable to believe that each class of AE signals represents one kind of damage mechanism, and the center of each class of AE signals reflects the basic physical information of corresponding damage mechanism. The AE energy is related to the energy released by the AE source, which is very important to discriminate the different mechanisms [14]. Frequency depends on the properties of composition involved in the micro-fracture process. Thus, cluster labeling can be proposed according to the Ab-energy and peak frequency [13].
Figure 6 illustrates the energy and peak frequency of the cluster centers of all the three samples. Classes A and B have similar frequency. Meanwhile, their AE energy are quite close. Figure 7 shows the typical waveforms and frequency spectra of each class of AE. It can be seen from Figure 7(a, b) that the typical waveforms of Class A and Class B are similar, which indicates that Class A and B should belong to the fracture of the same composition of C/SiC. Class A and B, exhibiting the characteristics of low frequency and energy, are associated with typical matrix cracking, which is consistent with the cracking of SiC matrix initiating at low stress due to its brittle nature [26]. Due to the larger damage area in matrix between fiber bundles, the corresponding AE energy and frequency are higher, it can be inferred that Class A corresponds to the matrix cracking between the fiber bundles, and Class B corresponds to the matrix cracking in fiber bundle. Class D contains AE signals with the highest energy and high frequency. From Figure 7(c, d), it is found that the waveform corresponding to Class D has a longer duration. Considering the local stress level and the released strain energy of fibers with few defects is higher than the matrix cracking, Class D is labeled as fiber cluster breakage (including single fiber and fiber cluster). Under compression load, the samples of stitched 2D-C/SiC have some delamination and interlayer friction, which have a high frequency. Thus, the unlabeled Class C is interlaminar delamination and friction.

### 4.4. Damage evolution of compressive specimens

Once all the AE events are classified, the damage evolution during the whole loading process can be described. The cumulative AE energy of each class varies with displacement and time is shown in Figure 8. It is found that the cumulative AE energy of Class D and Class C of all specimens increased

| Sample No. | Class | P-F(kHz) | Ab-E(attoJ) | Counts | RiseTime(μs) |
|------------|-------|----------|-------------|--------|--------------|
| All specimens | A | 33 | 69,712 | 60 | 141.5 |
| | B | 17 | 9325 | 23 | 187.1 |
| | C | 362 | 139,503 | 97 | 109.5 |
| | D | 70 | 1,142,726 | 76 | 124.5 |
| S1 | A | 22 | 24,445 | 49 | 152.6 |
| | B | 15 | 9282 | 23 | 302.2 |
| | C | 282 | 126,701 | 78 | 129.8 |
| | D | 55 | 986,899 | 59 | 125.9 |
| S2 | A | 41 | 66,505 | 71 | 105.1 |
| | B | 18 | 8220 | 20 | 79.6 |
| | C | 388 | 101,960 | 102 | 80.7 |
| | D | 113 | 1,236,052 | 104 | 114.0 |
| S3 | A | 37 | 97,804 | 62 | 147.9 |
| | B | 17 | 11,264 | 27 | 202.1 |
| | C | 401 | 201,392 | 107 | 129.5 |
| | D | 63 | 1,209,806 | 76 | 127.8 |

#### Table 2. AE features of the cluster centers.

![Figure 5](image-url) The SEM micrographs of the fracture surfaces: (a) Fiber cluster breakage, (b) Matrix crack between fiber bundles, (c) Matrix crack, (d) enlarged view of area A.
Figure 6. Ab-Energy and peak frequency of the four class AE centers of three samples.

Figure 7. Typical waveform and frequency spectra of each class of AE signals.
rapidly from 0.4 mm and 0.7 mm respectively. At the same time, it is observed that Class D and Class C were the main AE events during the compression tests.

Although it is found from Figure 8 that the damage development of the three specimens has a good consistency, the macroscopic fractures of the three specimens in Figure 3 have obvious differences. Since the samples were made of stitched C/SiC, the stitches have influence on the material properties and fracture location. Figure 9 is a schematic diagram of the stitches’ location near the fracture surfaces of the three samples. The direction of the stitches of S1 is consistent with the loading direction, and the span length of the stitches is uneven. The fracture surface appeared at the position with a larger span of stitches and ends near the stitches. The stitches of S2 and S3 are 90° to the loading direction, and the location of stitches in S3 is more even than that in S2. The fracture surface of S3 is between the two stitches. The fracture surfaces of S2 ran through two stitches at a position with a large distance between stitches, and finally ended near the other two stitches. Table 1 shows that the ultimate strength of S1 and S2 are 168.7 MPa and 167.3 MPa, respectively, while the ultimate strength of S3 is 185.4 MPa, indicating that the density and uniformity of the stitches have a greater impact on the strength of the material rather than the direction of the stitches. The fracture generally occurs in the sparse part of the stitches.

Each AE class’ events of three specimens during compression load were compared in Figure 10. It can be found that S1 and S3 have the most fiber cluster breakage events, while S2 has the most interlaminar delamination and friction events. At the same time, from the load displacement of about 0.7 mm in each sample, Class C began to increase sharply, and the Class B was almost saturated. Combined with the observation of Figure 8, The surge points of Class C and Class D are shown in Table 3. It is found that the compression damage process of the specimens can be roughly divided into three stages by the surge points of Class C and Class D.

The first stage (0 ~ 77MPa): Although the stress–displacement curve shows linear, some AE signals were collected. This indicates that there have micro-damages at the beginning of the loading. It is found from Figure 8 that the cumulative energy of AE signals is very low, indicating the damage size.

Figure 8. The development of cumulative AE absolute energy with crosshead displacement and time: (a)S1;(b)S2;(c)S3.
was small, such as single fiber breakage or short matrix cracks. This stage is defined as the initial damage stage.

The second stage (77 ~ 122MPa): Figure 10 shows that the growth rate of Class B began to decrease, indicating that after the initial damage development
and accumulation in the first stage, the propagation events of matrix cracking in fiber bundle gradually decreased. The matrix cracking between the fiber bundles represented by Class A continued to grow. The development of Class A caused the fibers to begin to break in the form of clusters, and the energy of fiber breaking is greatly increased. At the same time, this stage started with a sharp increase in the cumulative energy of Class D, but the cumulative events of Class D were basically unchanged. It further illustrated that the fiber damage events represented by Class D start to be dominated by the breakage of fiber cluster with larger damage area. This stage is defined as the damage development stage beginning with high-energy fiber cluster breakage.

The third stage (122MPa-failure): By observing Figure 10, it is found that the cumulative events of Class B almost stopped to increase at this stage, indicating that the matrix cracks in fiber bundle represented by Class B have been saturated. This stage started with the rapid increase in the number of Class C. At the same time, the fiber cluster breakage and the interlaminar delamination promoted each other. The corresponding Class D and Class C cumulative events both increased at a relatively large rate until the specimens fail. This stage is defined as a damage acceleration stage in which fiber cluster breakage and interlaminar damage develop rapidly.

After the stage analysis of the stitched C/SiC compression damage process is completed, the proportion of various AE events in the load process is counted, as shown in Table 4. It is found that the overall proportion of matrix cracks is stable, about 40% (in S1, S2 and S3: 41.6%, 40.5% and 38.6%, respectively). In S3 where the stitches are evenly distributed and denser, the fibers were mainly broken by fiber clusters with larger energy. The delamination damage was dominated by a small area of delamination expansion and friction. Therefore, AE events of Class C accounted for only 18.9%, while that of Class D accounted for 42.5%. It showed that the density and uniformity of the stitches have a great influence on the fiber fracture form and delamination damage during the compression damage process of stitched C/SiC composites.

5. Conclusion

(1) The stitched C/SiC prepared by the PIP process has four kinds of damage mechanisms: matrix cracking in fiber bundle, matrix cracking between fiber bundles, fiber cluster breakage, interlaminar delamination & friction. Among them, fiber cluster breakage and interlaminar delamination & friction are the main failure mechanisms, and the sum of the corresponding AE events accounts for about 60% of all AE events.

(2) Although the compression failure of stitched C/SiC has a large difference in the macroscopic fracture, the damage evolution process is relatively consistent. According to the development of the main damage mechanisms, it can be divided into three stages: the initial damage stage, the damage development stage, and the damage acceleration stage.

(3) The stitches have an obvious hindering effect on the interlaminar delamination during the compression damage process of the stitched C/SiC. Compared with the direction of the stitches, their spacing and uniformity have a greater impact on the form of fiber breakage and the size of the delamination. The failure generally occurs at the location where the stitches are sparse.

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