Fatigue failure warning method for needled ceramic matrix composite by acoustic emission monitoring

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Abstract. Ceramic matrix composite is a kind of mechanical engineering material with excellent high temperature mechanical properties, which has been widely used in aircraft propulsion system and thermal protection system. Therefore, it is of great significance to study the fatigue failure of needled ceramic matrix composite. In this investigation, based on the real-time acoustic emission (AE) monitoring of needled C/SiC ceramic matrix composite, the characteristics of AE energy during the fatigue damage process were obtained. In addition, considering the emission coefficient of AE energy and the threshold value of AE energy in single cycle, a method for judging the imminent fatigue failure of needled composite was proposed. By comparing the cycle of failure warning by proposed method with the experimental fatigue life, the proposed method can provide fatigue failure warning near and before fatigue failure.

1. Introduction
Ceramic matrix composite is a kind of mechanical engineering material with excellent high temperature resistance, high specific strength and high specific stiffness, which have been widely used in aircraft propulsion system and thermal protection system [1]. Therefore, it is necessary to study the fatigue failure warning method for needled C/SiC ceramic matrix composite under fatigue loading.

Sundaresan [2] studied the acoustic emission (AE) characteristics of hip prosthesis fabricated from carbon/thermoplastic composite under fatigue loading, which found that there is an inverse relationship between fatigue life and the level of acoustic emission activity. And the method to predict fatigue life by using AE energy and count was proposed. Nkrumah [3] investigated the relationship between accumulative AE energy and fatigue life, and found that there was an approximate power relationship between them. Momon [4] discovered a fixed proportion between the time of the minimum emission coefficient $R_{AE}$ and the fatigue life, and the residual fatigue life of SiC/[Si-B-C] and C/[Si-B-C] ceramic matrix composites was predicted by coefficient $R_{AE}$ method and Benioff’s law. Maillet [5] studied the energy release of AE source and the identification of characteristic critical time by using emission coefficient $R_{AE}$ and Benioff’s law. However, numerous small peaks and valleys can be found in the accumulative AE energy curve of needled ceramic matrix composite during whole fatigue damage process, which results in the difficulty to determine the occurring time of minimum $R_{AE}$ during monitoring process. Therefore, this study tried to avoid using the minimum $R_{AE}$ as the
damage parameter, and a new damage criterion that can provide warning before the failure of needled C/SiC composite was proposed based on the analysis of AE energy characteristics during the fatigue damage monitoring process.

2. Material and testing

2.1. Material
The material used in this investigation is needled carbon fiber reinforced silicon carbide matrix (needled C/SiC) ceramic matrix composite, which manufactured by chemical vapor infiltration process. The detail microstructure of needled C/SiC is shown in Figure 1. This composite includes 0° layers, 90° layers, short-cut fiber layers, and needled fiber bundles. Among them, the 0° layers and 90° layers are all long fiber layers (the fiber in 0° layer is parallel to the direction of external fatigue loading), and the short fibers in short-cut fiber layers are chaotical. In addition, the needled fiber bundles can improve the bearing capacity in the thickness direction.

The shape and dimensions of needled C/SiC composite specimen is shown in Figure 2.

![Figure 1 Microstructure diagram of needled C/SiC](image1)

2.2. Testing
The fatigue loading with stress ratio (the ratio of minimum fatigue load to maximum fatigue load) of 0 is applied by MTS hydraulic servo testing machine. And the load waveform is sine with the frequency of 1 Hz.

The AE detection system is AEwin system. In order to avoid air in the gap between AE sensor and needled C/SiC composite specimen, Vaseline was used as vacuum couplant. The AE sensor coated with Vaseline was fixed on the specimen by cloth based tape, and the fixed position of AE sensor is shown in Figure 2. In addition, for filtering out the noise irrelevant to the fatigue damage of needled composite specimen, the threshold value of AE amplitude is set as 45 dB.

![Figure 2 Shape and dimensions of needled C/SiC composite specimen (unit is mm)](image2)

3. Experimental results
The fatigue life of three needle C/SiC ceramic matrix composite specimens is obtained through the test. And the fatigue life of each specimen is listed in Table 1.
Table 1 Fatigue life of each needled C/SiC composite specimen

| Specimen | A1  | A2  | A3  |
|----------|-----|-----|-----|
| Fatigue life (cycles) | 86  | 523 | 797 |

Figure 3 Instantaneous AE energy of each needled composite specimen (a) Specimen A1 (b) Specimen A2 (c) Specimen A3

Figure 3 Accumulative AE energy (10^5 mV.ms) of each needled composite specimen (a) Specimen A1 (b) Specimen A2
Figure 4 Accumulative AE energy of each needled composite specimen

Through the dynamic AE monitoring of the fatigue damage process of needled C/SiC composite specimens, the evolution relationships of the instantaneous AE energy and the accumulative AE energy versus time were obtained, as shown in Figure 3 and Figure 4. From figures, higher AE energy was generated during the initial stage of fatigue damage and near final failure, while the AE energy during the intermediate stage of fatigue damage is relatively small. Therefore, the accumulative AE energy increases sharply in the initial stage, then tends to be stable, and finally increases rapidly again. As shown in Figure 4, the fatigue damage process of needle composite can be divided into three stages according to the trend of AE energy versus time.

In addition, refer to the investigation in Ref. [6], the damage modes of three stages during fatigue damage process can be judged preliminarily. For stage I, the accumulative AE energy increased sharply in the first few loading cycles. Therefore, it is considered that this stage corresponded to matrix cracking, fiber/matrix interface damage, large-scale cracking in 90° layers, and fibers failure with weak bearing capacity. For stage II, the increase of accumulative AE energy was relatively slow. Therefore, it is considered that the main damage modes were matrix cracking and fiber/matrix interface slip in both 0° layers and short fiber layers, and accompanied by a small amount of fiber failure. For stage III, it included near-failure or complete failure of composite specimen with obvious increase of accumulative AE energy, which may be resulted from matrix cracking, fiber/matrix interface slipping, and instantaneous broken of large number of fibers (especially the fibers in 0° layer). In addition, at the moment of complete fracture, some fibers in 90° layer were pulled out by adjacent 0° layer and broken.

4. Proposed fatigue failure warning method by AE energy

4.1. Calculate the AE energy generated in each cycle
The AE energy generated by each cycle can be calculated by accumulating the AE energy within the time of each cycle,

\[ E_n = \sum_{i=1}^{m} E_{n,i} \] (1)

where \( E_n \) is the AE energy generated by the \( n \)th fatigue loading cycle, \( E_{n,i} \) is the AE energy generated by the \( i \)th AE event belonging to the \( n \)th cycle. Among them, the total number of AE events included in the \( n \)th cycle is \( m \).

4.2. Calculate the emission coefficient of AE energy in each cycle
The \( R_{AE} \) has been proposed to characterize the emission coefficient of AE energy versus time [4]. But due to the serious fluctuation of \( R_{AE} \) versus time during the fatigue damage process of needled C/SiC composite, it is difficult to be used as a quantitative criterion for fatigue failure in engineering practice. Therefore, the emission coefficient of AE energy with respect to cycles was proposed, which is
where \( R_{AE}(n) \) is the emission coefficient of AE energy of the \( n \)th fatigue cycle, \( E_{\text{loading}} \) is the AE energy generated by the first cycle reaching the peak loading in the whole fatigue damage process. For experiments of this study, the first peak loading occurred in the first cycle. And the relationship between the emission coefficient \( R_{AE}(n) \) and cycles of each composite specimen is shown in Figure 5.

### 4.3. Criterion for fatigue failure warning

From Figure 4, it can be found that the \( R_{AE}(n) \) increased obviously in a short time near the failure of needled composite (stage III), which corresponded to the AE events with high energy occur. Although the overall trend of \( R_{AE}(n) \) in stage I and stage II present decrease and stability, respectively, a few sudden increases of \( R_{AE}(n) \) can also be found. However, the value of AE energy corresponding to the sudden increases of \( R_{AE}(n) \) in stage I and stage II, such as the point A in Figure 5(a) and the point B in Figure 5(c), are still smaller than that in stage III which tends to fail. And for peak values of \( R_{AE} \) in stage I and stage II, compared with the previous cycle, the increase is not very significant in usual. Therefore, according to above phenomena, a fatigue failure criterion used for AE monitoring can be proposed as

\[
R_{AE}(n_c) \geq \alpha R_{AE}(n_c - 1)
\]

\[
E(n_c) \geq E_{th}
\]

(3)

(4)

where \( n_c \) is the critical cycle near failure, \( R_{AE}(n_c) \) and \( R_{AE}(n_c - 1) \) are the emission coefficient of cycle \( n_c \) and cycle \( (n_c - 1) \), respectively, \( \alpha \) is the energy multiple of adjacent cycles \( (\alpha > 1) \), \( E_{th} \) is the AE energy threshold value of one cycle. And the values of \( \alpha \) and \( E_{th} \) can be empirically determined by the information of AE energy information during the fatigue damage process.

Since the critical cycle \( n_c \) is usually close to the fatigue life of the composite, \( n_c \) is taken as the warning cycle. In fact, \( n_c < N \) (\( N \) is the fatigue life of composite specimen), and only a little different between \( n_c \) and \( N \) in usual. Therefore, when the fatigue cycle reaches \( n_c \), it is necessary to carefully consider whether the needled composite can continue to serve safely.
5. Validation of fatigue failure warning

Relevant investigation [6] shows that when the composite is close to final failure, the AE energy can reach 2000–6000 mV·ms. Thus, the AE energy threshold value of one cycle $E_{th}=3000$ mV·ms is taken in this study. In addition, the AE energy increases sharply when close to final failure. Therefore, $\alpha=3$ is taken in this study. The fatigue life monitoring results are listed in Table 2. And the results show that using AE energy parameters as the criterion can effectively provide fatigue failure warning for needled C/SiC composite during AE monitoring process.

| Specimen | Warning critical cycle (cycles) | Experimental life (cycles) |
|----------|--------------------------------|---------------------------|
| A1       | 80                             | 86                        |
| A2       | 343                            | 523                       |
| A3       | 793                            | 797                       |

6. Conclusions

In this work, real-time AE monitoring for needled C/SiC ceramic matrix composite specimen subjected to fatigue loading was carried out. Through studied the trend of AE energy during the fatigue damage process and the fatigue failure criterion based on AE energy, the following conclusions are drawn.

1. During the fatigue damage process of needled ceramic matrix composite, the instantaneous AE energy is initially large, then small, and finally increases again. And the accumulative AE energy shows the characteristics of initial sharp increase, then slow and steady increase, and finally rapid increase again on the verge of fracture;

2. On the basis of considering the relationship of AE energy emission coefficient between adjacent cycles and AE energy threshold of one cycle, a failure warning criterion based on AE real-time monitoring was proposed, which can realize the function of early warning before composite final failure.

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