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Real-time evaluation of energy attenuation: A novel approach to acoustic emission analysis for damage monitoring of ceramic matrix composites

E. Maillet[a], N. Godin[a,*], M. R'Mili[a], P. Reynaud[a], G. Fantozzi[a], J. Lamon[b]

[a] *Insa-Lyon, Mateis CNRS UMR5510, F-69621 Villeurbanne, France*
[b] *CNRS, LMT ENS Cachan, F-94230 Cachan, France*

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Abstract

This paper proposes a new approach to the analysis of acoustic emission data. The energy of acoustic emission signals recorded at two sensors is used to evaluate real-time energy attenuation due to damage accumulation. The method is applied to acoustic emission data recorded during static fatigue tests at intermediate temperatures on ceramic matrix composites. The evaluation of energy attenuation appears as a new indicator for damage monitoring and lifetime prediction, the attenuation increase being attributed to transverse matrix cracks opening.

Keywords: Acoustic emission; Attenuation; Ceramic matrix composites; Durability

1. Introduction

The use of advanced composite materials in aeronautical structures has been constantly increasing for the past decades. One of the main current developments is the use of Ceramic Matrix Composites (CMCs) in the new generations of civil aircraft engines, owing to their low density and excellent mechanical properties at high temperatures. Although both fibers and matrix are made of brittle materials (mostly carbon or silicon carbide), CMCs can reach a high strain-to-failure (∼1%) due to energy dissipation resulting from multiple matrix cracking and deflection of cracks at fiber/matrix interfaces.[1] In static fatigue at high temperature under low stresses, composite ultimate failure involves oxidation-activated slow crack growth in fibers.[2] The development of self-healing matrices has allowed a considerable increase of CMCs lifetimes by reducing the effects of oxidation. Above 550 °C, in oxidizing atmosphere, the matrix produces a borosilicate glass that fills up cracks, therefore limiting the amount of oxygen reaching fibers. Expected lifetimes in service conditions are tens of thousands of hours, which can hardly be checked out using laboratory tests for practical reasons. Therefore, a real-time prediction of the remaining lifetime is necessary. It requires the monitoring of damage evolution for which acoustic emission (AE) is a suitable technique.

Acoustic emission refers to the energy released in the form of transient elastic waves when a material damages. The recording of surface displacements associated with such waves is also called acoustic emission. AE provides real-time information about damage, in terms of location and mode. It has been used to study the mechanical behavior of various types of CMCs under tensile loading.[3–5] Clustering techniques have also been applied to AE signals for a better understanding of the mechanical behavior of C/C composites,[6] SiC/SiC composites,[7,8] SiC_f/[Si–B–C] self-healing composites[9,10] and C_f/[Si–B–C] self-healing composites.[11] More recently AE-based methods were developed for lifetime prediction of CMCs in static fatigue.[12–14] The energy of AE signals was used as a measure of damage and the developed methods aimed at defining a single indicator for damage monitoring and prediction of remaining lifetime. Finally, the combination of Acoustic Emission with other nondestructive techniques has also been investigated for damage monitoring of CMCs. Among others, AE was combined with infrared thermography,[15,16] electrical resistivity[17] and acousto-ultrasonics.[8]

Elastic waves experience significant attenuation during propagation from an AE source to the sensors. Thus, attenuation can affect the ability to locate and identify AE sources. There are three main causes of attenuation: geometric spreading, material

* Corresponding author. Tel.: +33 472438073; fax: +33 472437930.
E-mail address: nathalie.godin@insa-lyon.fr (N. Godin).

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damping and wave scattering. In permanent testing conditions, attenuation due to geometric spreading and material damping remains unchanged but attenuation due to wave scattering may increase as a result of damage progression in particular in the form of transverse matrix cracks in the case of CMCs. Therefore, energy attenuation measurements can be used as indicator of damage growth. Acousto-ultrasonics measurements have been applied to evaluate the evolution of energy attenuation during load/unload/reload tensile tests on SiC/SiC composites.[18] A significant decrease of energy of the captured ultrasonic wave of over 50% was observed between undamaged and damaged states. The increase of energy attenuation was attributed to transverse matrix cracks opening, therefore providing an indicator for the monitoring of damage evolution. Evaluating attenuation during test using acousto-ultrasonics usually requires calibration tests. Also, using a single sensor gives a measure of the relative evolution of attenuation. Therefore, the present paper proposes a new approach for the evaluation of energy attenuation that uses the energy recorded from AE sources generated during material damage. The method is based on the calculation of the ratio of AE energy recorded for each source at both ends of the specimen using two sensors. A single indicator, the energy attenuation, is evaluated from thousands of local attenuation measurements obtained from the AE sources that are detected during tests. The present method uses the AE data recorded during tests and therefore it can complete the existing AE data analysis methods such as damage localization or data clustering for damage mode identification, whereas traditional ultrasonic measurements would require additional tests. The method is applied in this paper to damage monitoring during 8 static fatigue tests on SiC_f/[Si–B–C] composites. Since attenuation measurements are obtained in situ, future applications of this new approach may involve taking into account effects of propagation on the recorded AE signals to better define AE sources and improve damage mode identification.

2. Materials and experimental procedure

2.1. Material

The SiC_f/[Si–B–C] composite (Herakles-Safran Group) was made of woven PyC coated SiC fibers (Hi-Nicalon, Nippon Carbon Ltd., Japan) and a multilayered [Si–B–C] matrix produced via chemical vapor infiltration. A seal coat protected the material. Fiber volume fraction was 35–40% and porosity was about 12 vol%. Dog-bone shaped specimens were machined. Their total length and thickness were respectively 200 mm and 4.5 mm. The gauge section had a length of 60 mm and a width of 16 mm.

2.2. Mechanical testing

Fatigue tests were performed under constant load on a pneumatic tensile machine, which was designed to ensure reliable control of specimen deformation during long duration tests while reducing environment noise. Before loading, specimens were heated up to the test temperature (450 or 500 °C) at a rate of

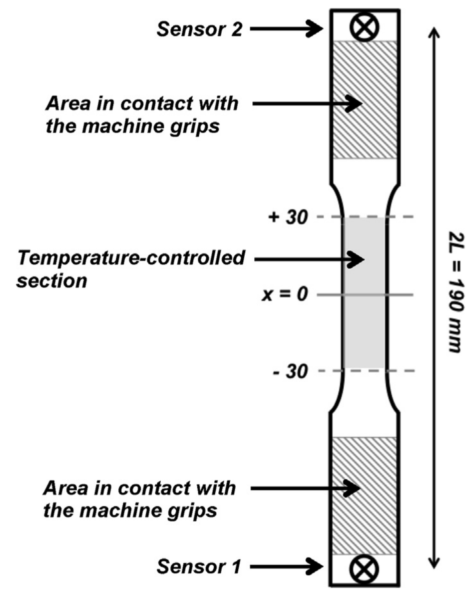

Fig. 1. Set-up for static fatigue tests at high temperature.

20 °C/min. These temperatures are critical for the lifetime of this composite system because they allow subcritical crack growth in the fibers but no self-healing of the matrix. After 1 h at the test temperature, specimens were loaded at a rate of 600 N/min up to the test load selected in the range of 40–95% of the rupture load (indicated for each test in terms of stress as the ratio σ/σ_r). The rupture load (and the rupture stress σ_r) was determined from tensile tests under monotonous loading at room temperature for a reference sample of each batch. An extensometer was used for elongation measurement. The machine was equipped with a 25 kN load cell.

2.3. Acoustic emission monitoring

Two sensors (micro80, Physical Acoustics Corporation) were positioned, 190 mm apart, on the specimen (Fig. 1). This configuration was selected in order to limit the temperature to which the sensors were subjected. The sensors were placed in housings machined in the grips. A holding system with spring was used in order to maintain constant contact pressure between sensors and material throughout test. Medium viscosity vacuum grease was used as a coupling agent. Each sensor was connected to a preamplifier (gain: 40 dB, frequency range: 20–1200 kHz), which was connected to the data acquisition system (two-channel MISTRAS 2001, Physical Acoustics Corporation). The threshold was set to 32 dB in order to filter out signals from ambient noise. The acquisition parameters were set as follows: peak definition time 50 μs, hit definition time 100 μs and hit lockout time 1000 μs. These values were optimized before test so as to obtain consistent AE signal parameters (rise time, duration, energy, . . .) for similar artificial sources (Hsu-Nielsen sources). For each AE signal, the following data were recorded: arrival time (first threshold crossing), stress and strain values, as well as signal energy. Signal energy was defined as $\int u(t)^2 dt$ where $u(t)$ is the signal voltage. Wave velocity V (9500 m/s) was determined