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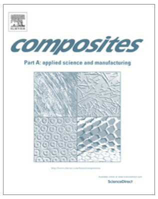

Combined acoustic emission and multiple lead potential drop measurements in detailed examination of crack initiation and growth during interlaminar testing of ceramic matrix composites

Yogesh P. Singh [*], Rabih Mansour, Gregory N. Morscher

Department of Mechanical Engineering, The University of Akron, Akron, OH 44325-3903, USA

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ABSTRACT

This article presents a novel approach in which the methods of acoustic emission and direct current potential drop are utilized as complimentary techniques to monitor crack initiation and growth in interlaminar testing of ceramic matrix composites. The method presented here can be used in localizing cracks, monitoring of crack growth, and has potential to reveal the nature of damage. It is argued that using the first derivative of time dependent electrical resistance/potential drop provides information on individual events during the failure of a ceramic matrix composite under different types of loading. The results discussed here pertain to a particular method of testing for interlaminar properties of ceramic matrix composites. However, the use of presented approach can be extended to other testing methods and materials.

1. Introduction

Ceramic matrix composites (CMCs) are promising candidates for aerospace applications, such as the hot section components of turbine engines, due to their low density and excellent high temperature strength [1,2]. The damage in a fiber reinforced CMCs can occur in several different ways. Some examples include transverse and/or longitudinal matrix cracks, interfacial debonding, fiber breakage, and delamination among others [3–8]. Understanding, detecting, and monitoring different types of damage are essential in achieving optimal performance from components made out of CMCs. Conventional and modal Acoustic Emission (AE) methods have become popular in the evaluation of failure in different types of composite materials e.g., carbon fiber reinforced polymers (CFRPs) [9–13], and CMCs [14]. The method of Electrical Resistance/Potential Drop (ER/PD) is another technique which has shown potential to be used as insitu monitoring of damage in composite materials with a conductive phase [15–19]. In the past decade, there has been significant success in utilizing modal AE for damage evaluation in CMCs [14,20,21]. However, the full potentials of ER/PD have not been realized, especially in CMCs.

Despite of their potential to provide significant details of damage, AE and ER techniques have some limitations. For example, AE being a passive technique requires it to be used in situ during mechanical loading. In other words, AE cannot be used in damage evaluation of components after service. The requirement of using AE in situ also may limit its use in high temperature applications. Furthermore, in some applications there are stringent requirements to be followed in placement of AE sensors. For instance, the use of AE sensors for locating cracks requires at least two sensors (preferably three) placed far apart with cracks occurring in between. In addition, the dispersive nature of wave propagation in CMCs significantly attenuates the AE signals. Similarly, ER/PD technique is limited by the fact that it is sensitive only to the damages which result in changes in the current path. Thus, ER/PD might not detect significant events unless there is an associated alternation of current path. Moreover, it requires the materials to be conductive in order for ER/PD technique to work. The measured change in ER/PD frequently has poor resolution due to the scatter in data. This can be attributed to either poor contact between the electrically conducting surfaces or the limited resolution of the instrument being used in recording the data.

ER can serve as a good method to capture overall behavior of crack propagation in a component under loading [22,23] but, to best of our knowledge, capturing information about individual events and their location has not been attempted using the technique of ER/PD before. In this work, we show that far more additional details about mechanical damage can be obtained by using a combination of AE and the proposed ER/PD derivative methods.

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[*] Corresponding author.
E-mail address: ysingh@uakron.edu (Y.P. Singh).

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These details include identifying the damage source and pinpointing its location. In addition, we also discuss the optimization of ER/PD technique for acquiring more reliable data by reducing lead contact resistance and improving the sensitivity of the technique by the use of multiple ER lead configuration.

The results discussed here are from a wedge-loaded double cantilever beam (DCB) interlaminar fracture testing of CMC specimens. The choice of such a test is based on the simplicity of damage/crack morphology during interlaminar testing. Nonetheless, the proposed monitoring methods can, in principle, be extended to other types of testing and for different composite materials with at least one conductive phase.

2. Experimental

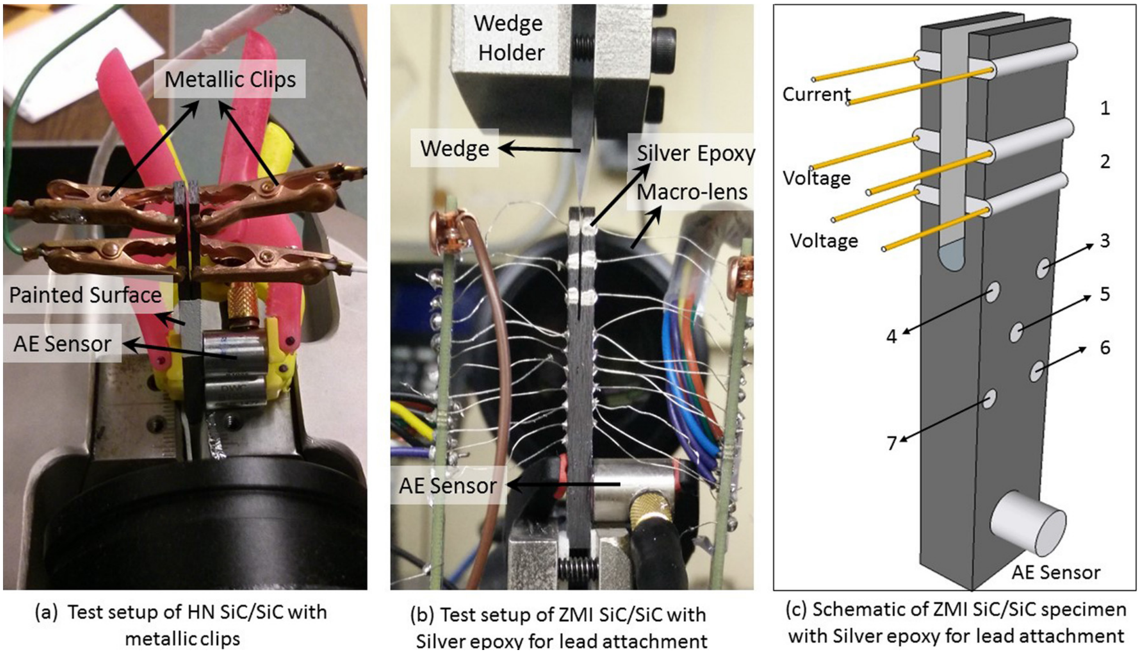
We employed a wedge-loaded DCB testing method [24,25] to initiate and propagate an interlaminar crack along the length of the specimens. Two material systems were used in this study, both were prepared through a slurry-cast melt-infiltration process and only differed in their fiber type [26]. The first system (HN SiC/SiC) contained Hi-Nicalon™ fibers, while the other consisted of Tyranno ZMI fibers (Ube Industries, Kyoto, Japan). Both systems consisted of 16 plies of balanced 0°/90°, five-harness-satin woven fiber preforms with Boron Nitride coating. The fiber resistivity of Hi-Nicalon was 14 Ω mm [27] while the bulk resistivity of HN SiC/SiC composite was measured to be 0.1 Ω mm. Similarly, the resistivity of ZMI fiber was 20 Ω mm [18] while the bulk resistivity of composite in this case was measured to be around 0.2 Ω mm. The resistivity of the BN interphase is in the order of 10^{13} Ω mm. This suggests that in both of these systems the matrix is the most conductive phase. The higher conductivity of melt-infiltrated matrix is ascribed to the presence of free silicon due to processing.

The pictures from the actual test setup and a schematic of specimen with multiple leads attached on specimen surface using silver epoxy is shown in Fig. 1. Specimens HN SiC/SiC (Fig. 1(a)) were 80 mm in length, 5 mm in width and 4 mm in thickness while ZMI SiC/SiC specimen (Fig. 1(b)) had dimensions of 50 mm × 5 mm × 4 mm. A notch of width ~0.40 mm and a length of about one third of the total specimen length (25 mm for HN SiC/SiC and 15 mm for ZMI SiC/SiC) was machined on each specimen in the midplane.

The HN SiC/SiC specimens were tested in an MTS machine Model 43 (with 30 kN load cell), while the ZMI SiC/SiC specimen was tested in an Instron 5582 machine (with 500 N load cell). During testing, the specimens were held in a vertical position over ~5 mm in the bottom grip of the testing machine. For the purpose of propagating the interlaminar crack, a silicon nitride wedge with 18° head angle was inserted into the notch. The wedge was supported in the top grip of the machine which allowed its vertical displacement at a constant rate of 1 mm min^{-1}, thereby creating a splitting force and forcing a crack at the sharpest end of the notch.

Optical microscopy was used to monitor crack growth on one surface of the specimen. The surface was painted white prior to the testing to provide better resolution of the crack tip location. A camera connected to a macro-lens took pictures at a rate of 0.5 Hz. The analysis of the captured images provided the time dependence of surface crack growth.

To measure ER/PD, the method of four co-linear probes was utilized. In the initial phase of testing four metallic clips (copper) were attached on the arms of the HN SiC/SiC specimens as shown in Fig. 1(a). The two outer clips (one on each arm) served as the current leads while the potential difference was measured between the two inner clips. Placement of current leads on the arms of the specimen ensures that the current flows from one arm to the other by going through the thickness of the specimens. Some modifications were implemented in testing of the ZMI SiC/SiC specimen. Instead of using the metallic clips, a two-component curable silver epoxy was used to attach copper wires on the specimen surface to ensure a good electrical contact throughout the testing. Extra contacts were also placed along the length of the specimen at different locations on the surface (Fig. 1(b) and (c)). In addition to two pairs of leads on arms (other than the current leads), five extra pairs of leads on the surface of the specimen were used as shown in Fig. 1(b). The five pairs of leads beyond the notch were placed in such a way that for every



(a) Test setup of HN SiC/SiC with metallic clips

(b) Test setup of ZMI SiC/SiC with Silver epoxy for lead attachment

(c) Schematic of ZMI SiC/SiC specimen with Silver epoxy for lead attachment

Fig. 1. Test setup for (a) HN SiC/SiC and (b) ZMI SiC/SiC specimens. Also shown in (c) is a schematic picture of lead placement using silver epoxy for ZMI SiC/SiC specimen. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)