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Frictional heating in a unidirectional fibre-reinforced ceramic composite

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Holmes and Shuler [1] recently found that significant internal heating occurs during the cyclic loading of fibre-reinforced ceramics. In their investigation, conducted with cross-ply carbon fibre/SiC matrix composites (hereafter referred to as C_f/SiC), it was observed that the extent of internal heating was strongly influenced by the peak fatigue stress and loading frequency. For example, during ambient-temperature fatigue between fixed stress limits of 250 and 10 MPa, the temperature rise measured at the specimen surface ranged from approximately 0.5 K at a sinusoidal loading frequency of 1 Hz to over 30 K at 85 Hz. For a fixed loading frequency of 75 Hz and minimum stress of 10 MPa, the temperature rise ranged from 0.8 K at a peak stress of 50 MPa to 28 K at a peak stress of 250 MPa. It was proposed that the temperature rise observed during cyclic loading was caused by the frictional sliding of fibres within the matrix [1]. Because of the significant mismatch in thermal expansion coefficients that exists between the fibres and matrix, C_f/SiC composites contain extensive processing-related matrix cracking [2]. Fatigue loading of these initially microcracked specimens would promote interfacial debonding; once debonding occurs, internal heating would occur by the repeated frictional sliding of fibres along the fibre–matrix interface.

For a composite that is initially free of matrix cracking, and assuming a mechanism of internal heating involving the frictional slip of fibres within debonded zones, internal heating should begin when a stress level that is sufficient to initiate matrix cracking is reached (at lower stress levels internal heating should be absent). To provide experimental evidence for this mechanism of internal heating, the present investigation utilized a simpler unidirectional fibre-reinforced ceramic that was initially free of matrix cracking. As discussed below, a simple experiment which involved monitoring the specimen temperature, while sequentially increasing the peak fatigue stress until matrix cracking initiated, was used to investigate the relationship between matrix cracking and internal heating.

A 16-ply unidirectional Nicalon fibre/calcium aluminosilicate matrix composite (hereafter referred to as Nicalon/CAS-II) was chosen for this investigation (material processed by Corning Glass Works, Corning, New York, USA). The composite, formed by hot-pressing, had a nominal fibre content of 35 vol %. Edge-loaded tensile specimens (see Fig. 1) with a 33 mm gauge length were machined from the billet, using diamond tooling. After polishing the specimens to a finish of 0.5 μm using diamond paste, microscopy was used to verify that the specimen was initially free of surface cracking (sectioning of a similarly prepared specimen was used to verify that the machining operation did not cause internal matrix cracking). Fatigue testing was conducted on an MTS model 810 servohydraulic load frame (Materials Test Systems, Minniapolis, Minnesota, USA) equipped with self-aligning hydraulic grips. Details of the gripping arrangement used for the fatigue testing of similar edge-loaded specimens has been discussed elsewhere [3]. All fatigue experiments were conducted under load control using a 25 Hz sinusoidal waveform. Using a water-cooled chamber, which surrounded the specimen and grips, the air temperature in the vicinity of the specimen was maintained at 293 ± 0.1 K. The temperature of the specimen was measured using a high-resolution infrared pyrometer that was focused to a diameter of 5 mm at the centre of the specimen gauge section

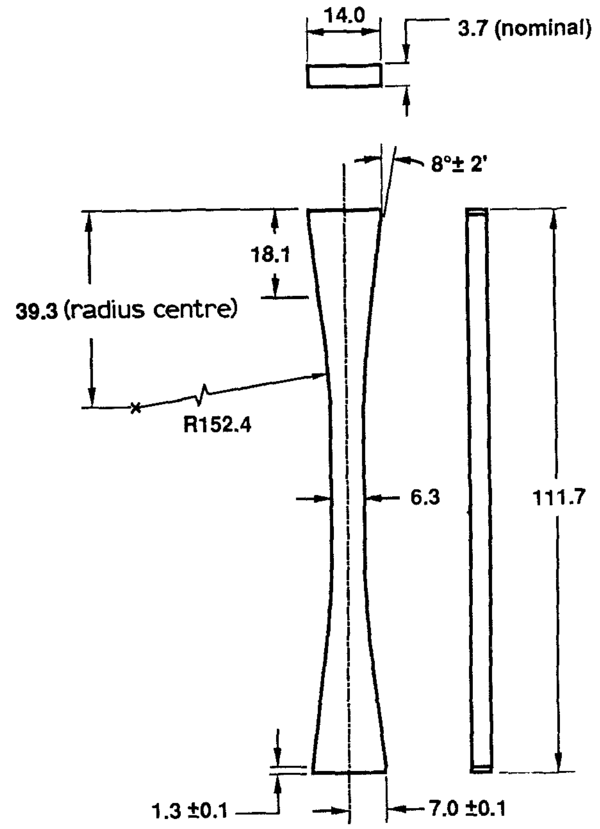

Figure 1 Specimen geometry used to investigate internal heating under tension–tension fatigue loading (all dimensions in mm).

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(Everest Interscience Inc., Fullerton, California, USA, model 5402). The pyrometer had a resolution of 0.1 K and a response time of 300 ms.

Under monotonic tensile loading at 293 K the composite exhibited an initially linear response, followed by a gradual decrease in stiffness at a stress of approximately 225 MPa (Fig. 2). Following the nomenclature introduced by Prewo and co-workers [4, 5], the decrease in specimen stiffness at 225 MPa will be referred to as the proportional limit strength. Physically, the proportional limit is caused by a detectable amount of matrix cracking. Initial matrix cracking during monotonic or cyclic loading can occur at much lower stress levels; the compliance change that accompanies this initial microcracking is, however, typically below the resolution of mechanical extensometers.

To determine if the onset of internal heating coincides with the initiation of matrix cracking, and to provide information regarding the influence of matrix crack spacing and stress range on the extent of heating, an experiment was conducted wherein the peak (maximum) fatigue stress was increased in 20 MPa steps from 100 to 260 MPa (see Fig. 3). During this experiment, the minimum fatigue stress was held constant at 10 MPa. At each stress level the specimen was fatigued for 25 000 cycles. The initiation of matrix cracking, and subsequent change in crack spacing at higher peak stresses, was determined by obtaining surface replicas of the specimen edge after the first fatigue cycle and at the completion of each 25 000 cycle fatigue block. All replicas were taken with the specimen loaded to a stress of 10 MPa. From the results of this experiment, neither matrix cracking or internal heating was observed at a peak stress of 100 MPa. However, after the first fatigue cycle at a peak stress of 120 MPa several matrix cracks were found in the specimen gauge section; after 25 000 cycles at this stress, the average crack spacing was approximately 2 mm. Coinciding with the initiation of matrix cracking at 120 MPa, a maximum temperature rise of 0.3 K was detected (see Fig. 4). Fig. 5 provides a summary of the heating and cooling curves obtained for peak fatigue stresses between 120 and 240 MPa. The relationship between maximum temperature rise, matrix crack density and peak fatigue stress is given in Fig. 6.

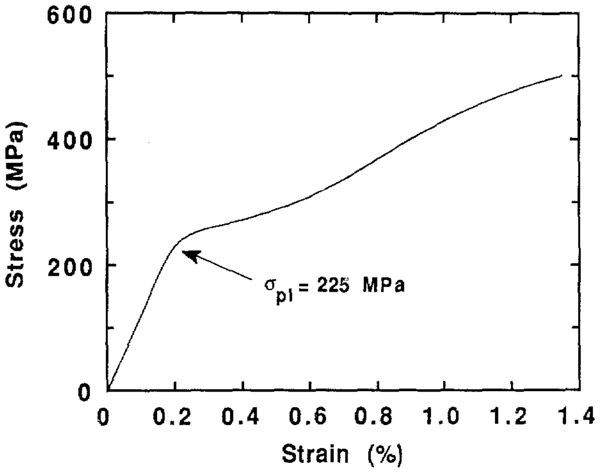

Figure 2 Monotonic tensile behaviour of Nicalon/CAS-II at 293 K. The test was performed at a constant loading rate of 100 MPa s^{-1}.

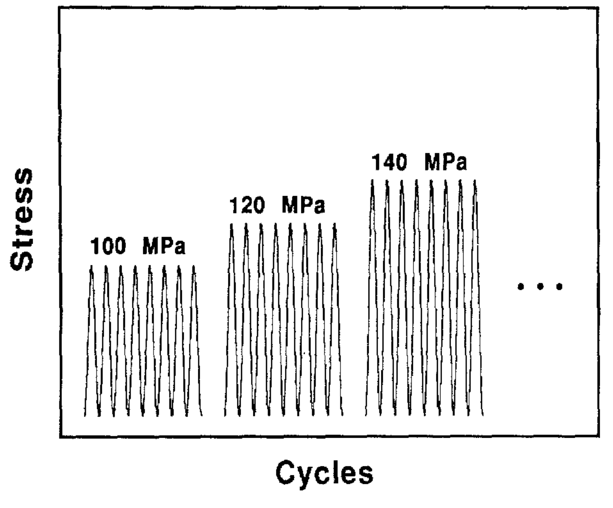

Figure 3 Loading sequence used to establish the relationship among frictional heating, matrix cracking and peak fatigue stress. The minimum stress was fixed at 10 MPa and the frequency at 25 Hz.

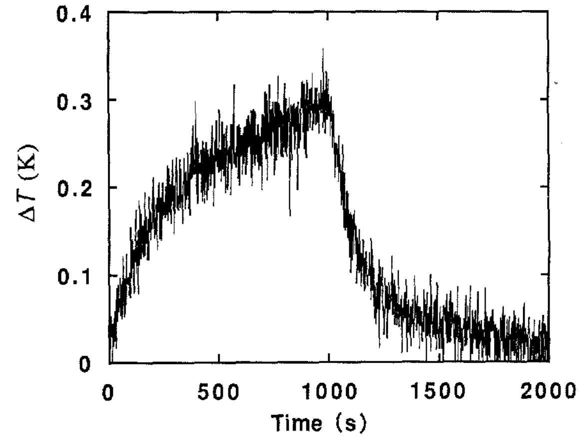

Figure 4 Initiation of frictional heating in Nicalon/CAS-II. Coinciding with the onset of matrix cracking, a temperature rise of 0.3 K was first observed at a peak stress of 120 MPa. The initial temperature of the composite was 293 K.

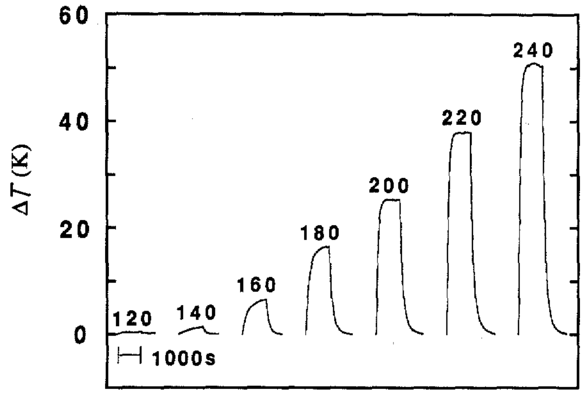

Figure 5 Stress dependence of frictional heating in Nicalon/CAS-II. Fixing the loading frequency at 25 Hz and the minimum stress at 10 MPa, the peak fatigue stress was increased in 20 MPa steps from 100 to 260 MPa. A temperature rise was first detected at a peak stress of 120 MPa (see Fig. 4), with specimen failure occurring at 260 MPa. The initial temperature of the composite was 293 K.

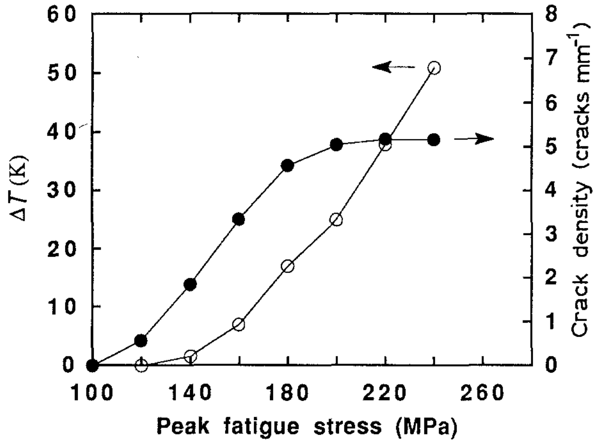

Figure 6 Temperature rise and matrix crack density (reciprocal of mean crack spacing) in Nicalson/CAS-II versus peak fatigue stress. The crack density reached an approximate plateau near 220 MPa. The minimum fatigue stress was 10 MPa. The initial temperature of the composite was 293 K.

Corresponding to a significant increase in the number of matrix cracks, a sharp increase in temperature rise (to approximately 1.8 K) occurred at a peak stress of 140 MPa. At a peak stress of 240 MPa the temperature rise approached 50 K. Increasing the peak fatigue stress to 260 MPa resulted in specimen failure within 1000 cycles. Between 220 and 240 MPa, which is in the vicinity of the initial proportional limit strength of 225 MPa, the crack density approached saturation (Fig. 6); for both stresses the mean crack spacing was approximately 190 μm (a micrograph showing typical matrix cracking at 220 MPa is given in Fig. 7). Since the crack spacing was similar at these two stress levels, the further increase in temperature rise at 240 MPa can be attributed to the increase in stress range; an increase in the length of the debonded slip zones along the fibre–matrix interface could also contribute to the additional temperature rise (note that the extent of interfacial debonding is primarily influenced by the maximum tensile stress [6–8]).

As noted above, a temperature rise of 0.3 K was first detected at a peak stress of 120 MPa. Although a slight residual strain offset and increase in specimen compliance occurred at 120 MPa (see Fig. 8), measurable stress–strain hysteresis was not observed until a peak stress of 160 MPa was reached. Thus, conventional techniques for detecting the onset of fatigue damage (e.g. by monitoring changes in stress–strain behaviour using mechanical displacement transducers) may not be sensitive enough to detect the initial stages of fatigue damage in fibre-reinforced ceramics. The results of this study indicate that careful monitoring of specimen temperature may provide a more accurate approach for detecting the onset of microstructural damage during cyclic loading. These results also indicate that fatigue damage in fibre reinforced ceramics can initiate at peak stress levels which are substantially below the monotonic proportional limit strength.

Frictional heating is considered to be a fundamental mechanism of energy dissipation that occurs during the cyclic loading of fibre-reinforced ceramics. Since interfacial debonding typically accompanies matrix cracking [6–8], the correlation found between initial matrix cracking and the onset of internal heating strongly suggests a mechanism of internal heating that involves the frictional slip of fibres within debonded slip zones. It is not clear at present whether frictional heating is caused primarily by the slip of fractured fibres or whether the slip of unfractured fibres also contributes to heating. Further analytical and experimental work is required to separate the relative contributions to frictional heating from the slip of fractured and unfractured fibres. For a mechanism of internal heating involving the frictional slip of fibres, it should be possible to relate the work expended in the frictional sliding of fibres to the increase in specimen temperature during cyclic loading. If this can be successfully accomplished, measurement of the temperature rise during cyclic loading could provide a convenient

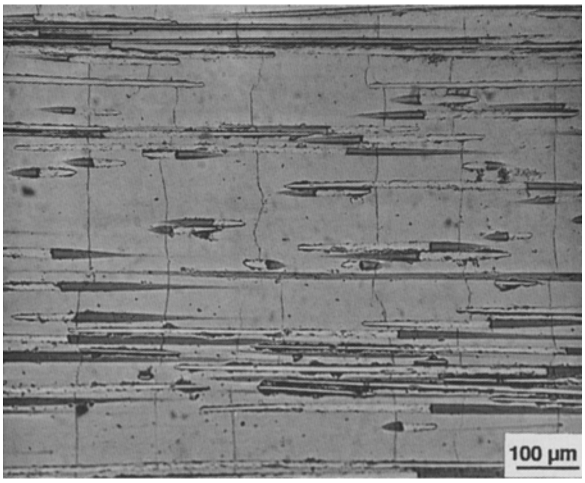

Figure 7 Optical micrograph of an acetate film replica showing typical matrix cracking observed along the specimen edge after 25 000 cycles at a peak stress of 220 MPa. The loading direction is from left to right in the plane of the micrograph.

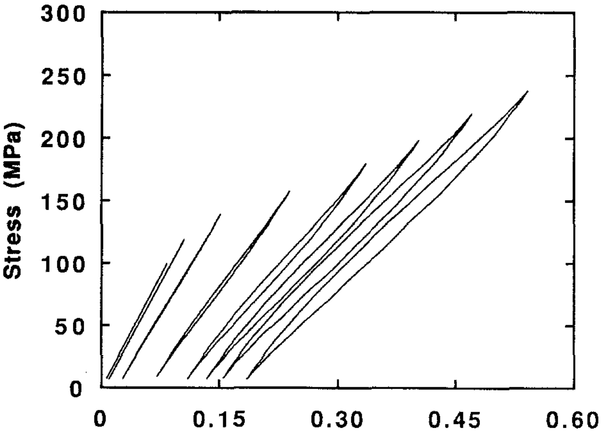

Figure 8 Cyclic stress–strain behaviour of Nicalon/CAS-II determined during the incremental loading experiments described in Fig. 3. The curves shown were obtained at the end of each 25 000 cycle fatigue block. Comparison of Figs 5 and 8 shows that an initial temperature rise was measured before the development of significant stress–strain hysteresis at 160 MPa.

technique to supplement other methods, such as fibre pushout [9–11] and pullout experiments [12–14], which are currently used to estimate the level interfacial shear that exists in fibre-reinforced ceramics.

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