SELF-MONITORING OF STRAIN AND DAMAGE BY A CARBON-CARBON COMPOSITE

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Introduction

Carbon, though more high-temperature resistant than a polymer, is more brittle than a polymer. Thus, there is a need to monitor the condition of a carbon-carbon composite structure. This monitoring is conventionally conducted by acoustic emission, which is capable of detecting substantial cracking, but not slight cracking. In contrast, this paper addresses the use of the carbon-carbon composite itself as the damage sensor to monitor the composite's own damage (i.e., to self-monitor the damage), using the increase in electrical resistivity as a measure of the irreversible composite damage.

The monitoring of reversible strain is useful for structural control. Embedded or attached strain sensors are conventionally used for strain monitoring, though they suffer from poor durability and, in the case of embedded sensors, they have the tendency to degrade the mechanical properties of the structure. In contrast, we have employed the carbon-carbon composite itself as the strain sensor to monitor the composite's own strain (i.e., to self-monitor the strain), based on the reversible increase of the electrical resistivity of the composite upon tensile straining.

Experimental

The carbon-carbon composite, provided by Sigri Great lakes Carbon Corp. (Union, NJ) under the grade designation of CC 1501G, was in the form of a sheet containing carbon fiber roving fabric (90° biaxial weaving) and was produced by lamination and compression. The heat treatment was at 2000°C. According to the manufacturer, the bulk density was 1.40 - 1.45 g/cm^3, the open porosity was 20-25%, the bending strength was 210-250 MPa, the dynamic modulus of elasticity was 60-65 GPa, the interlaminar shear strength was 9-12 MPa and the ash content was 0.08%. According to our measurement, the tensile strength was ~ 382 MPa.

The electrical resistance R was measured in the direction of one of the two perpendicular sets of fibers using the four-probe method while tension was applied in the same direction. Silver paint was used for electrical contacts. The four probes consisted of two outer current probes and two inner voltage probes. The resistance R refers to the sample DC resistance between the inner probes. The four electrical contacts were placed around the whole perimeter of the sample in four parallel planes that were perpendicular to the stress axis, such that the inner probes were 60 mm apart. The specimen was of length 85 mm, width 6.80 mm and thickness 2.46 mm. The stress axis was along the longest dimension of the specimen. One strain gage was attached to the center of one of the two opposite large surfaces of a specimen to measure the strain in the longitudinal direction. Two strain gages were attached to the centers of the two opposite large surfaces of a specimen to measure the strain in the lateral direction. Two other strain gages were attached to the two opposite small surfaces to measure the strain in the thickness direction. The strains from each pair of strain gages were averaged. The average strains were used to calculate the Poisson's ratios in the lateral and thickness directions.

Results and Discussion

Fig. 1 shows the fractional resistance increase $\Delta R/R_0$ during first cyclic tension to 360

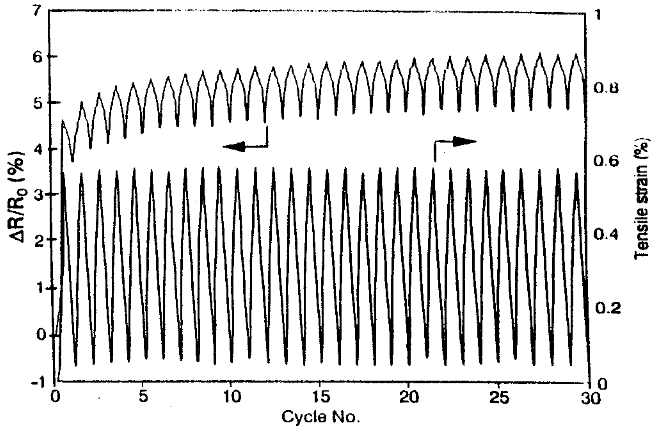

Fig. 1 $\Delta R/R_0$ vs. cycle No. and tensile strain vs. cycle No. during first cyclic tension.

MPa. The strain was almost totally reversible. The irreversible strain was 0.040% at the end of the first cycle, and increased slightly with increasing cycle number. $\Delta R/R_0$ increased upon loading in every cycle, such that it irreversibly increased slightly after every cycle and the irreversible increase in $\Delta R/R_0$ was particularly large for the first cycle. At fatigue failure, $\Delta R/R_0$ abruptly increased.

Measurement of $\Delta R/R_0$ during cyclic tension was performed at various stress amplitudes. The reversible part of $\Delta R/R_0$ increased significantly with increasing stress amplitude, and less significantly with increasing cycle number. The irreversible part of $\Delta R/R_0$ was much smaller than the reversible part of $\Delta R/R_0$ at a stress amplitude of 30% of fracture stress, but exceeded the reversible part of $\Delta R/R_0$ at higher stress amplitudes. The irreversible part of $\Delta R/R_0$ increased with stress amplitude much more significantly than the reversible part of $\Delta R/R_0$. As the stress amplitude was increased beyond 90% of fracture stress, both the reversible and irreversible parts of $\Delta R/R_0$ increased abruptly. Both these parts increased with cycle number, but the effect was small compared to that of the stress amplitude.

The reversible part of $\Delta R/R_0$ is mainly due to reversible dimensional changes and correlates with reversible strain. The irreversible part of $\Delta R/R_0$ is due to damage. Although the decreases in irreversible strain and modulus also indicate damage, the changes in these parameters are very small compared to the change in the irreversible part of $\Delta R/R_0$. The great sensitivity of the irreversible part of $\Delta R/R_0$ to damage is also shown by the significant non-zero value of the irreversible part of $\Delta R/R_0$ after merely the first cycle, even at a stress amplitude of just 20% of the fracture stress. However, the incremental rise in irreversible $\Delta R/R_0$ beyond ~ 500 cycles was small. The composite damage probably involved fiber-matrix interface weakening, matrix cracking and fiber breakage; these origins of damage could not be distinguished through the experimental technique used. Nevertheless, the increase of the irreversible part of $\Delta R/R_0$ as cycling progressed provided a continuous indication of the extent of damage. That the reversible part of $\Delta R/R_0$ also increased with cycling and that an abrupt increase of the irreversible part of $\Delta R/R_0$ is associated with an abrupt increase in the reversible part of $\Delta R/R_0$ suggest that the reversible part of $\Delta R/R_0$ is partly associated with a phenomenon which intensifies as damage increases, although it is mostly associated with dimensional changes. This phenomenon may be reversible crack opening during tension, as cracks aggravate with cycling.

Conclusions

A carbon-carbon composite was able to sense its damage and dynamic strain, as its resistance increased irreversibly due to damage and increased reversibly upon tensile elastic straining. The damage sensitivity was so high that even damage after the first cycle of tensile loading within the elastic regime was detected. The reversible resistance increase upon reversible straining was mainly due to dimensional changes, but it was partly due to a phenomenon that intensified as damage increased. The strain gage factor was 1.2-2.4.