§19. Cryogenic Mixed-Mode Fatigue Delamination Growth of Composite Insulation Systems for Superconducting Magnets

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1. Purpose

Woven glass fiber reinforced polymer (GFRP) composite laminates provide good electrical and thermal insulation together with adequate load-carrying ability and are used as insulation and structural support in superconducting magnets. In laminated composites, delamination is one of the major failure modes. Various external loadings or manufacturing defects (e.g., matrix voids) can cause delaminations in laminated composite structures which can reduce the ability of the structures to withstand load. Hence, understanding of initiation and propagation of delaminations under static and cyclic loads at cryogenic temperatures is essential for damage tolerant design of cryogenic composite structures. The purpose of this work is to investigate the mixed-mode I/II fatigue delamination growth behavior in woven GFRP laminates at cryogenic temperatures.[1)]

2. Procedure

In this work, National Electrical Manufacturers Association (NEMA) grade G-11 woven GFRP laminates were employed for the tests. The specimens for the mixed-mode bending (MMB) tests were produced from panels of G-11 woven laminates. The panel had a thickness of 3.85 mm. The specimen length and width were 70 and 20 mm, respectively, and the specimens were cut with the length parallel to the warp direction. A polymer film was placed at the specimen midplane which serves as a delamination initiator.

The mixed-mode I/II fatigue delamination tests were conducted using a MMB apparatus.[2)] The G-11 specimens were tested at room temperature, liquid nitrogen temperature (77 K) and liquid helium temperature (4 K). All fatigue tests were performed in sinusoidal load control at a test frequency of 2 Hz and a constant load ratio R of 0.1. The load ratio is defined as $R = P_{\min}/P_{\max}$, where $P_{\max}$ and $P_{\min}$ are the maximum and minimum applied loads, respectively. The compliance was generated for all corresponding values of the number of cycles N, and the delamination length a was monitored using the relationship between compliance and delamination length. After the fatigue delamination tests, microscopic observations of the specimen fracture surfaces were made with scanning electron microscopy (SEM).

The test specimen and apparatus were modeled using ANSYS finite element code. The orthotropic elastic properties of G-11 woven laminates for the finite element analysis were determined from the micromechanics model. Fatigue delamination growth under mixed-mode loading is typically described in terms of a power law relationship:

$$\mathrm{d}a/\mathrm{d}N = A(\Delta G_T)^m, \qquad (1)$$

where ΔG_T is the range of the total energy release rate G_T, i.e., the sum of Mode I, Mode II and Mode III energy release rates (G_{I}, G_{II}, G_{III}) for the MMB test, and A and m are constants determined from the curve fit to the fatigue test data. The virtual crack closure technique (VCCT) was used to calculate the Mode I, Mode II and Mode III components of the energy release rate.

3. Results

Fig. 1 presents the plot of delamination growth rate da/dN versus total energy release rate range ΔG_T data at room temperature (RT), 77 K and 4 K for $G_{\mathrm{II}}/G_T = 0.53$. The lines in the figure represent the power law relationships. The delamination growth rates at 77 K and 4 K are lower than that at room temperature. Also, the delamination growth behavior is influenced by the mixed-mode ratio of Mode I and Mode II. In addition, the hackle pattern on the fracture surfaces becomes more pronounced with an increasing component of Mode II loading, and the delamination growth mainly occurs by fiber/matrix debonding.

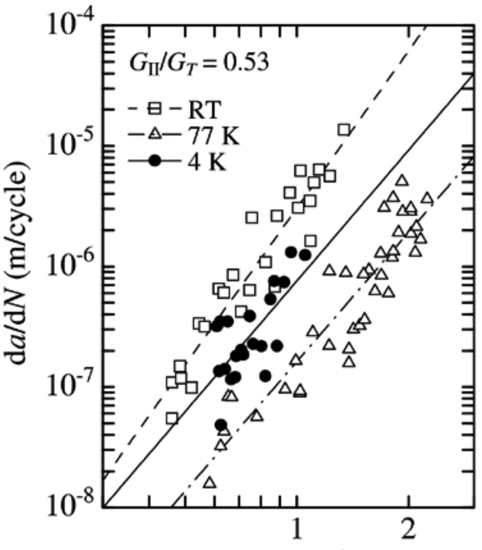

Fig. 1. Delamination growth rate da/dN versus total energy release rate range ΔG_T for $G_{\mathrm{II}}/G_T = 0.53$.

1) Shindo, Y. et al.: Comp. Sci. Tech. **71** (2011) 647.
2) Shindo, Y. et al.: Eng. Fract. Mech. **75** (2008) 5101.