§11. Cryogenic Shear-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. Delamination in composites often results in the loss of their stiffness and strength, which may lead to catastrophic failure of the structures. Hence, understanding of initiation and propagation of delaminations under cyclic loads at cryogenic temperatures is essential for damage tolerant design of cryogenic composite structures. The purpose of this work is to investigate the fatigue delamination growth behavior in woven GFRP laminates under combined sliding shear Mode II and scissoring shear Mode III loading at cryogenic temperatures.

2. Procedure

National Electrical Manufacturers Association (NEMA) grade G-11 woven GFRP laminates were employed for the tests. The woven GFRP panel for the test specimens was 3.85 mm thickness. A polymer film was inserted in the middle of the panel to act as a delamination initiator. The panel was cut into the specimens with a length of 38 mm and with three different widths of B = 36, 44 and 52 mm, respectively. Fig. 1 presents the six-point bending plate (6PBP) test setup. The test specimen was supported at four points and loaded at two points. In order to change the mixed-mode II/III ratio, the load span length s was adjusted according to the relation $s = B - 8$ mm. That is, for the specimen widths of B = 36, 44 and 52 mm, the load span lengths s were 28, 36 and 44 mm, respectively. The initial delamination length a_0 was about 9 mm.

The mixed-mode II/III fatigue delamination tests were performed under load control with constant amplitude at room temperature, liquid nitrogen temperature (77 K) and liquid helium temperature (4 K). The load cycle was sinusoidal and the ratio of the minimum applied load to the maximum applied load (load ratio) was equal to 0.1. The applied load was measured by the testing machine load cell. Also, the cyclic frequency was 2 Hz. After the fatigue delamination tests, microscopic observations of the specimen fracture surfaces were made with scanning electron microscopy (SEM).

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 6PBP test, during cyclic loading was calculated from a three-dimensional finite element analysis. The Mode I, Mode II and Mode III components of the energy release rate were determined using the virtual crack closure technique (VCCT). The delamination growth rate data were then expressed in terms of the total energy release rate range.

3. Results

The delamination growth rate appears to decrease as the temperature decreases from room temperature to cryogenic temperatures. Fig. 2 shows the SEM micrograph of the fracture surface at 4 K for the Mode III fraction G_{III}/G_T = 0.56 (s = 36 mm). The fracture surface is characterized by the presence of fiber/matrix debonding and matrix hackles between the fibers. Hackles are formed by microcracking in the resin material just ahead of the delamination front. Also, the hackles are inclined to the direction of delamination propagation and the hackle orientation angle depends on the Mode III fraction.

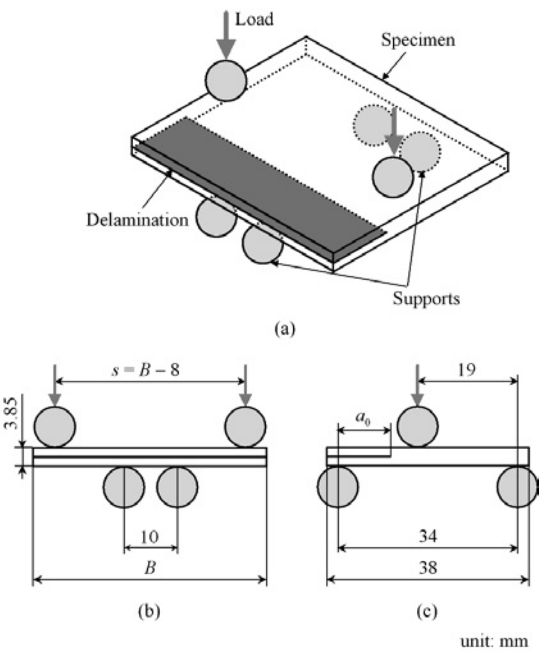

Fig. 1. (a) Perspective, (b) front and (c) side views of the 6PBP test setup.

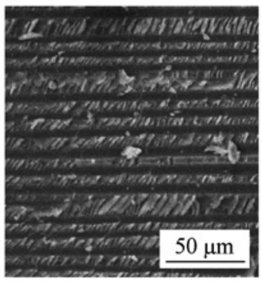

Fig. 2. Fracture surface at 4 K for G_{III}/G_T = 0.56 (delamination growth from left to right).