§25. Cryogenic Mixed-mode Interlaminar Fracture Toughness of Composite Insulation Systems for Superconducting Magnets

Shindo, Y., Narita, F., Takeda, T. (Dept. of Mater. Processing, Graduate School of Engineering, Tohoku Univ.), Sanada, K. (Dept. of Mechanical Systems Engineering, Faculty of Engineering, Toyama Prefectural Univ.),
Nishimura, A., Tamura, H.

1. Purpose

Laminated fiber reinforced polymer composites have attracted a wide range of uses in civil, automotive and aerospace applications on account of their superior tailor-made properties that are not attainable from conventional material. In particular, woven glass fiber reinforced polymer (GFRP) composite laminates show excellent mechanical and electrical properties and are candidate insulating systems for the superconducting magnet coils of fusion devices, such as the International Thermonuclear Experimental Reactor (ITER) and future nuclear fusion reactors.

Delamination is known to be the most critical fracture mechanism that limits fiber composite's load-carrying capability. The remote loadings applied to composite components are typically resolved into interlaminar tension and shear stresses that create mixed-mode delaminations. In addition, woven GFRP laminates undergo damage when subjected to mechanical loads at cryogenic temperatures, and the damage in these materials affects their cryogenic interlaminar fracture properties[1]. Therefore, better understanding of the mixed-mode interlaminar fracture and damage behavior of woven GFRP laminates at cryogenic temperatures is very useful for the structural design and development of materials. The purpose of this work is to experimentally and analytically investigate the interlaminar fracture and damage behavior of woven GFRP laminates under mixed-mode loading at cryogenic temperatures using the improved mixed-mode bending (MMB) test[2].

2. Procedure

In this work, G-11 woven glass/epoxy laminates manufactured by Arisawa Mfg. Co., Ltd., Japan (EL-762H) were used as specimen material. The specimen length (L) was 70 mm; the width (B) was 20 mm; and the thickness ($2H$) was 3.65 mm. These specimens were cut with the length parallel to the warp direction. A nonadhesive insert was placed at the mid-plane.

The improved MMB test apparatus was used to determine the energy release rates at the onset of delamination crack propagation for G-11 woven laminates at cryogenic temperatures. Different ratios of Mode I to Mode II loading at the crack tip can be imposed by varying the lever arm length (c), and the lever arm lengths of 12.5, 19.0 and 25.2 mm were selected in the present study. The MMB tests were conducted at room temperature, liquid nitrogen temperature (77 K), and liquid helium temperature (4 K) using a 30 kN capacity servo-hydraulic testing machine. The critical load (P_c) used in the determination of the energy release rate at the onset of delamination growth in mixed-mode was obtained as the load value at the point where the compliance (C) increased by 5 % or the load reached a maximum value, depending on which occurs first along the load-displacement curve. After the tests, all specimens were split completely in order to examine the fracture surfaces by scanning electron microscopy (SEM).

The three-dimensional finite element model of the improved MMB test was developed using ANSYS finite element code. In this investigation damage in the woven GFRP specimens was addressed using failure criteria and stiffness degradation technique. Our fiber-dominated failure predictions were based on the Hoffman failure criterion. The maximum strain failure criterion was used to predict matrix failure. When damage was predicted to occur, elastic moduli in the damaged elements were reduced according to the stiffness degradation scheme. The energy release rates for the undamaged state were obtained by the virtual crack closure technique. The total energy release rates for the damaged state were computed using the path-independent integral approach.

3. Results

Damage in woven GFRP specimens under mixed-mode loading at cryogenic temperatures is mainly related to the matrix microcracking, and the mixed-mode energy release rate at cryogenic temperatures are affected by damage within the specimen. The finite element analysis data showed that the damage causes an increase in the energy release rate. The predicted damage pattern is consistent with the observed damage zone in the tested specimen. Fig. 1 shows an example of the damage zones on the specimen surface at 4 K for the Mode II fraction (fraction of Mode II to total energy release rate) of about 0.76, the initial delamination length a_0 = 12.9 mm and the critical load P_c = 0.770 kN. In addition, the mixed-mode energy release rate increases with an increasing component of Mode II loading. This is mainly due to the formation of hackles.

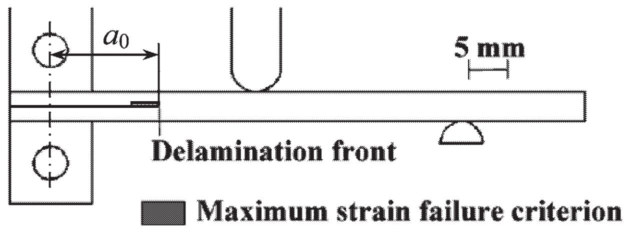

Fig. 1. Illustration of the predicted damage in the specimen at 4 K.

1) Shindo, Y. et al.: Cryogenics **49** (2009) 80.
2) Shindo, Y. et al.: Eng. Fract. Mech. **75** (2008) 5101.