§7. Development of Strength Evaluation Methods of Material Systems for Superconducting Fusion Magnets

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1. Cryogenic fracture properties and specimen size effects of structural alloy

Subsize CT (compact tension) specimens are being used to determine the cryogenic fracture toughness of structural alloys for superconducting fusion magnets. The benefits associated with the use of subsize CT specimens cannot be realized, however, without demonstration of a proper correlation between the test results for subsize and standard specimens. A correlation is necessary due to the change in specimen behavior when subsize CT specimens are used. This study examines the effects of test specimen size on the cryogenic fracture toughness properties of a nitrogen-strengthened austenitic stainless steel for superconducting magnet structures in fusion energy systems[1]. Elastic-plastic fracture toughness J_{IC} tests were performed on plane and side-grooved CT specimens ranging in thickness from 5 to 25 mm in liquid helium at 4 K. J-resistance (J-R) curves were generated by the single specimen unloading-compliance test technique. A three-dimensional finite element analysis was also conducted to investigate the effects of specimen thickness and side-groove on the through thickness distributions of the J-integral values. The results of the finite element analysis are used to supplement the experimental data.

Based on the numerical and experimental study, the following conclusions are advanced: (1) Since J-integral varies across the thickness of the plane specimen, the crack front after crack growth is curved. The crack size requirements of 4-K J_{IC} test standard are violated. (2) The straighter crack front resulting from side-grooving aids in the accurate prediction of crack extensions with unloading compliance techniques. (3) For the side-grooved specimen, the distribution of J-integral at the crack front is relatively uniform compared to that in the plane specimen. (4) The 4-K fracture toughness is independent of specimen size for the side-grooved CT specimens.

2. Acoustic emission and fracture behavior of GFRP woven laminates at cryogenic temperatures

The severe environment associated with superconducting fusion magnets poses numerous materials science and technology challenge. There are a variety of applications where GFRP (glass fiber reinforced polymer) woven laminates can provide thermal insulation, electrical insulation, structural support, and permeability barrier. The reliability and safety of an operational fusion reactor are entirely dependent on good design which in turn relies heavily on predictable materials performance. The objective of this study is to present results from an analytical and experimental study of the effects of temperature and geometrical variation on the critical values of the fracture mechanics parameters for GFRP woven laminates[2].

The CT specimens of notch length a_0 were machined from the G-11 woven laminates with different thickness, i.e. B=10.0, 12.5 and 25.0 mm thick. The width W was kept constant at 50 mm. CT tests were conducted at room temperature, liquid nitrogen temperature (77 K) and liquid helium temperature (4 K). During the CT tests, AE (acoustic emission) method was implemented.

For CT specimens, J-integral at the onset of unstable crack extension, J_C, was obtained from ASTM E 1820-01 and JSME S001-1992 as

$$J_C = J_{el} + J_{pl} \qquad (1)$$

where J_{el} and J_{pl} are elastic and plastic components of J_C, respectively. The J_{el} is determined by the expression

$$J_{pl} = (2 + 0.522 b_0 / W)\frac{U_p}{B b_0} \qquad (2)$$

where U_p is the plastic component of the work done and b_0 is the uncracked ligament (b_0 = W - a_0). The experimentally determined critical load P_M or P_A was used to determine the critical fracture mechanics parameters. P_M is the maximum load, and P_A is defined by knee point in the cumulative distribution of AE energy.

In order to evaluate the J_{el}, a three-dimensional linear finite element analysis was carried out. Effective elastic moduli were determined from a micromechanics model under the assumption of uniform strain inside the RVE (representative volume element). Critical load levels, and the geometric and material properties of the test specimens were input data for the analysis.

Table 1 shows the comparison of the J_C obtained from different critical loads. The superscripts M and A denote the values at P_M and P_A, respectively. It is observed that values of J_C^A are independent of the specimen thickness. On the other hand, values of J_C^M are strongly influenced by specimen thickness. The J_C^M varies in a non-systematic way with specimen thickness at room temperature and 77 K. The J_C^A increases between room temperature and 77 K, and further cooling to 4 K produces J_C^A decrease.

Table 1 Comparison of J_C at the different critical loads

Temp.	B (mm)	J_C^M (kJ/m^2)	J_C^A (kJ/m^2)
R.T.	10.0	18.80	14.37
	12.5	16.75	13.05
	25.0	14.68	12.39
77 K	10.0	42.68	38.51
	12.5	52.09	38.78
	25.0	39.28	37.21
4 K	10.0	46.08	34.28

References

1) Shindo, Y. et al., Proc. of the 39th JSME Tohoku Branch Congress, (2004), 46
2) Sumikawa, M. et al., Proc. of the 53rd Nat. Cong. of Theoretical & Applied Mechanics, (2004), 143