§17. Mechanical Properties of Candidate Materials for the Large-Scale Superconducting Magnets at Cryogenic Temperatures

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1. Cryomechanics of Insulating Materials

In order to evaluate the tensile properties of glass-cloth/epoxy laminates for superconducting magnets in fusion energy systems, tensile tests were examined both experimentally and analytically1). The tensile tests were conducted in accordance with JIS K 7054 at room temperature and liquid nitrogen temperature (77 K). The general specimen geometry was a rectangular dog-bone shape with constant gage length, but with each specimen size having a different specimen width B. The specimen was both edge-loaded from the grips by contacting the specimen shoulders with the specimen holder (test fixture I), and face-loaded by blocks (friction-type wedge grips) that squeeze the grip region (test fixture II). The JIS K 7054 test specimen is designed to be tested using friction-type wedge grips (test fixture II). There are inherent problems, however, with utilizing these friction wedge grips at cryogenic temperatures. The primary problem is that the specimen slips out of test grips during testing. This problem is avoided by using test fixture I. In the dog-bone shape specimens failure is always in the fillet, presumably because of a stress concentration there. The tensile strength increases as specimen width B is reduced. Failure of the specimen with B=15 mm is preceded by matrix microcracking at gage section while the specimen with B=25 mm shows no such features.

The experimental finding provides the data for analytical modeling. The model utilizes two damage variables which are determined from experimental data. A two-dimensional finite element analysis was also used to study the stress and damage distributions within the test specimens and to interpret the experimental measurements. The damage parameters are determined from stress-strain curves at room temperature (test fixture II) and 77 K (test fixture I). With the aid of a numerical tool such as the finite element method, the nonlinear response of composite structures to damage can be conveniently and effectively quantified. The calculated stress-strain curve at 77 K is in close agreement with the experimental data obtained by using test fixture I. The damage contours show that damage is qualitatively in line with the experimental observations. For cryogenic tension testing (test fixture I) of woven glass-epoxy laminates the narrow specimen must be used to obtain adequate test results. Analyses of other transition radii might suggest even more desirable specimen geometries. Although the use of a large radius specimen in test fixture II is recommended, the specimen slips out of the test grips during testing at 77 K.

2. Cryogenic Fracture Toughness of Structural Alloys and Weldments

The small punch (SP) test has been used successfully to characterize the cryogenic fracture toghness of base and weld metals with specimens measuring 0.5 mm in thickness2). This study was performed to demonstrate the feasibility of performing liquid helium temperature (4 K) SP tests on austenitic stainless steel weld for LHD superconducting magnets. The SP specimens (10×10×0.5 mm) were prepared from the different locations of electron-beam weld in type 316 stainless steel to examine the variation of the fracture properties in the weld fusion zone and the heat affected zone. Correlations between SP energy, equivalent fracture strain, and elastic-plastic fracture toughness were assessed. A finite element analysis was also performed to convert the experimentally measured load-displacement data into useful engineering information. The criterion for fracture used is the strain energy density (strain energy absorbed per unit volume) required to produce crack initiation in a solid, uncracked specimen. The maximum strain energy density was calculated and correlated with fracture toughness. The heat affected zone with high Vickers hardness at room temperature shows lower fracture toughness, compared to other regions.

References

1) Kumagai, S. et al. : Cryogenic Engineering **35**(2000)482..

2) Shindo, Y. et al. : ASTM Journal of Testing and Evaluation **28**(2000) 431.