§34. Cryomechanics of Structural Materials for Large Superconducting Magnets

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i) Purpose

Fusion energy reactors with superconducting magnets will require cryogenic structural alloys with improved combination of yield strength and fracture toughness at 4K. For austenitic stainless steels used in structural components of superconducting magnets, elastic-plastic fracture toughness (J_{IC}) evaluations at 4K are usually required for quantification of base metals. In structural alloy tensile specimens undergoing mechanical work in a liquid helium bath, internal temperature increases are favored by their low specific heat and thermal conductivity at this temperature. The possible occurrence of such heating must be considered in testing structural materials for liquid helium temperature applications.

In this study, we consider the cryogenic fracture behavior of an elastic-plastic material and the energy dissipation associated with crack extension. Fracture toughness and fractgraphic data are presented for an austenitic stainless steel plate tested at liquid helium temperature. Temperatures of a specimen were also measuted during straining at 4K. The specimen behavior is simulated numerically using the finite element technique. We estimate the associated temperature field. These estimates provide a useful guide for interpreting experimental results.

ii) Experiment and analysis

In order to evaluate the fracture toughness and the temperature rise, J_{IC} tests were performed with 1T compact tension specimens at liquid helium temperature. These tests were conducted in accordance with ASTM E813-81 and E813-87 for determining J_{IC} using the unloading compliance technique to monitor crack growth. Adiabatic heating was detected by measuring the internal temperature at a distance X_0 from the load line at the specimen midthichness using thermocouples embedded in the ligament along the fracture plane. Two positions of X_0, 33(No.1) and 37(No.2)mm, are studied.

For comparison, the specimen fracture behavior was calculated using the Dugdale model and the incremental theory. The dissipated energy can be calculated from the change in total elastic strain energy of the specimen during crack extension. We assume that 100% of the dissipated energy is converted into heat. We analyze the transient temperature state near the propagating heat source and include the effects of temperature-dependent material properties.

iii) Results

For the single specimen J_{IC} tests according to ASTM E813-87, we need the side grooved specimen to obtain the J_{IC} value. The predicted load-displacement response and J values matched experimental result very well. At time t_d, the load drop corresponding to the pop-in occurred. The experimental result for the temperature at the position of the thermocouple (No.1) is shown in Fig.1 as continuous line. The predicted temperature in crack extension using the incremental theory is also shown as dashed line.

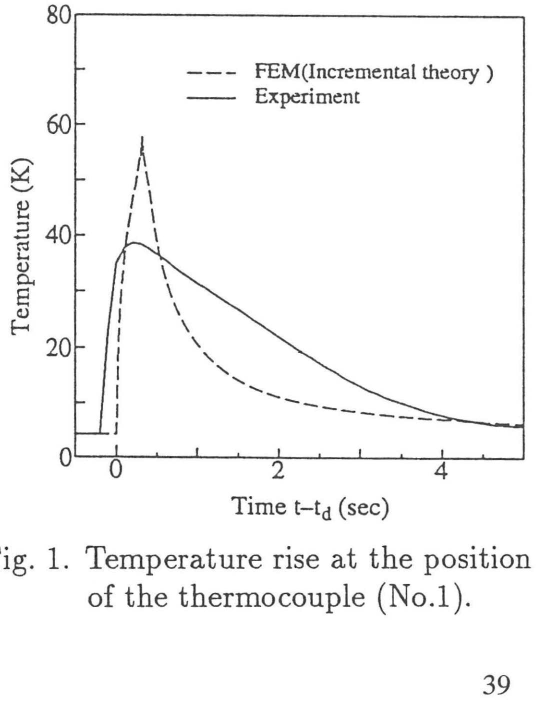

Fig. 1. Temperature rise at the position of the thermocouple (No.1).