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Specimen size effects in the cryogenic fracture toughness testing of Fe–12Cr–12Ni–10Mn–0.24N stainless steel

Y. Shindo*, K. Horiguchi, J. Yamada

Department of Materials Processing, Graduate School of Engineering, Tohoku University, Aoba-yama 6-6-02, Sendai 980-8579, Japan

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Abstract

This paper 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. Single-specimen *J*-integral tests were performed on CT (compact tension) specimens with and without side-grooves in liquid helium at 4 K. The aspect ratio (specimen width to thickness) and thickness were varied. 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.

Keywords: Fracture mechanics; Compact tension; Finite element analysis; Austenitic stainless steel; Liquid helium temperature; Superconducting fusion magnets

1. Introduction

Superconducting fusion magnets require cryogenic structural alloys with improved combinations of yield strength and fracture toughness in liquid helium at 4 K. The Japan Atomic Energy Research Institute (JAERI) has instituted a substantial alloy development program involving several steel companies [1,2]. Type JJ1 austenitic stainless steel [Fe–12Cr–12Ni–10Mn–0.24N (wt.%)] is one of a family of newly developed cryogenic structural steels to meet the JAERI fusion research goals of combined 1000 MPa yield strength and 200 MPa m$^{1/2}$ plane-strain fracture toughness (K_{IC}) at 4 K. Recently, Shindo and Horiguchi [3] evaluated the fracture toughness and the adiabatic heating of newly developed cryogenic structural steels at 4 K.

The first cryogenic standard for elastic–plastic fracture toughness (J_{IC}) test appeared in 1998 (JIS Z 2284 [4]) as a direct result of the U.S.–Japan Cooperative Program for Development of Test Standards. The standard uses compact tension (CT) specimens with fatigue precracking. Standard specimens are 25-mm thick (B) and 50-mm wide (W), with $W/B = 2$.

* Corresponding author. Tel.: +81 22 217 7341;
fax: +81 22 217 7341.
E-mail address: shindo@material.tohoku.ac.jp (Y. Shindo).

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Alternative specimens have $2 \le W/B \le 4$. Subsize CT specimens are also being used to determine the cryogenic fracture toughness of Ni–Fe superalloy sheath for superconducting fusion magnets [5]. 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.

Side grooves are highly recommended in room-temperature J_{IC} tests when the compliance method of crack length prediction is used [6]. 4-K J_{IC} tests of types JJ1 and JN1 austenitic stainless steels showed that side grooves reduced the end-of-test disparity between compliance-predicted and physically measured crack extension values of the standard and alternative CT specimens [3]. Yet, similar side grooving in 4-K tests of SUS304 actually prevented valid tests because the load drops then were too large to permit four unloading points within the 0.15-mm and the 1.5-mm exclusion lines [4]. Therefore, side grooving in 4-K J_{IC} tests is an option to be considered case-by-case in full awareness of the potential advantages and disadvantages.

The objective of this paper is to investigate the effects of specimen size on the 4-K fracture toughness of type JJ1 austenitic stainless steel. J_{IC} tests were performed on plane and side-grooved CT specimens ranging in thickness from 5 to 25 mm 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 performed to compute directly the J-values. The numerical findings were then correlated with the experimental results.

2. Experimental procedure

2.1. Material and specimens

Material used in the study is a 110-mm thick plate of type JJ1 austenitic stainless steel [7]. The material was melted in an electric-furnace, subjected to a vacuum oxygen decarburization process. A cylinder (1050-mm diameter and 1685-mm length) was produced by electroslag remelting, then forged to a 300-mm thick plate and hot rolled to a 110-mm thick plate. The plate was solution treated at 1328 K for 159 min prior to water quenching. The chemical composition of this material is given in Table 1. Following JIS Z 2277 [8] method, 4-K tensile properties were measured using 7-mm diameter round bar specimens. These specimens were located at 14 mm from the top surface of the 110-mm thick plate to the center of the specimen and machined in the transverse orientation, such that the fracture plane orientation matched that of the CT specimens described below. The yield strength σ_{YS}, ultimate tensile strength σ_{TS}, effective yield strength $\sigma_Y = (\sigma_{YS} + \sigma_{TS})/2$, and Young's modulus E obtained for the test material at 4 K are shown in Table 2.

Table 2
Mechanical properties of test material at 4 K

σ_{YS}(MPa)	σ_{TS} (MPa)	σ_Y (MPa)	E (GPa)
1072	1579	1326	201

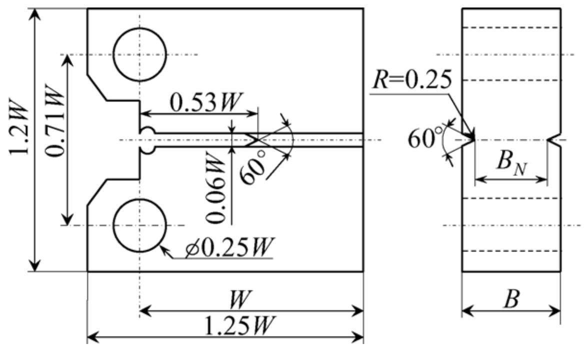

Fig. 1. CT specimen used in J_{IC} tests.

Fig. 1 shows the CT specimen geometry. The thicknesses for 1T and 0.5TCT specimens having a width-to-thickness ratio ($W/B = 2$) were 25 mm and 12.5 mm, respectively. The 0.2TCT specimen was 5-mm thick and 25-mm wide, with $W/B = 5$. The widths of both

Table 1
Chemical composition of test material (wt.%)

C	Si	Mn	P	S	Ni	Cr	Mo	Fe	N
0.01	0.5	9.93	0.022	0.003	11.78	11.62	4.8	Bal.	0.237