Cryogenic fracture and adiabatic heating of austenitic stainless steels for superconducting fusion magnets

Yasuhide Shindo*, Katsumi Horiguchi

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

Received 25 April 2003; revised 22 May 2003; accepted 1 July 2003

Abstract

This paper discusses the fracture and the adiabatic heating of austenitic stainless steels that may be used in cryogenic structures for the superconducting magnets of magnetic fusion reactors. Elastic–plastic fracture toughness tests were performed on compact specimens in liquid helium at 4 K. Adiabatic heating was detected by measuring the internal temperature. The effect of test specimen size and side grooving on the cryogenic fracture toughness, and the temperature rise during dynamic crack growth are examined. A size independent toughness parameter results in the case of side-grooved specimens. The effect of inclusion content on the fracture mechanics parameters is also discussed.

Keywords: Fracture mechanics; Cryomechanics; Toughness testing; Compact specimens; Austenitic stainless steels; Liquid helium temperature; Fracture toughness; Adiabatic heating; Superconducting magnets; Magnetic fusion reactors

1. Introduction

Research on cryogenic structural materials primarily supports the development of magnetic confinement systems for magnetic fusion such as International Thermonuclear Experimental Reactor (ITER). July 2001 marked the end of the nine year period established for the Agreement on Co-operation in the Engineering Design Activities (EDA) for the ITER [1]. In ITER, the plasma is confined and shaped by a combination of magnetic fields from three main origins: toroidal field coils, poloidal field coils and central solenoid coils. Aiming in ITER at steady-state operation, all the coils are superconducting.

Fusion energy applications demand superior properties from structural materials. For magnet casings, the material must be stable at liquid helium temperature (4 K), and possess high strength and toughness. The projected requirements as proposed by the Japan Atomic Energy Research Institute (JAERI) are the yield strength of 1000 MPa and plane-strain fracture toughness ($K_{IC}$) value of 200 MPa m$^{1/2}$ for the base metal at 4 K, and similar properties in the welded condition [2]. Types JN1 and JJ1 austenitic stainless steels are emerging as the preferred structural materials for superconducting fusion magnet casings designed to operate at 4 K [3].

For structural alloys used in components of superconducting magnets, fracture toughness evaluations at 4 K are usually required for qualification of base metals and welds. Two acceptable methods of quantitative fracture toughness measurement under elastic–plastic conditions are the $J$-integral and crack-tip-opening displacement (CTOD) tests. Existing standards (such as ASTM E 1820 [4] and ISO 12135 [5]) were established primarily on the basis of room temperature experience. New or revised standards are necessary because special considerations apply near absolute zero where self-heating is severe, and plastic deformation is unstable. The unstable plastic deformation (discontinuous flow) is free-running process occurring in localized regions at higher than nominal rates of strain with internal specimen heating. Typically, the load versus displacement record in liquid helium is composed of continuous and discontinuous deformation stages. At first the deformation is stable with smoothly rising loads. As testing continues, alternating periods of stable and unstable loading form a series of serrations on the load versus displacement curves. At each serration, plastic deformation and tearing occurs abruptly at fast,
uncontrolled rates, and load reduction ensues until the instability is arrested. The serrations are faint at first but steadily increase in magnitude. The first cryogenic standard for elastic–plastic fracture toughness \( (J_{IC}) \) test appeared in 1998 (JIS Z 2284 [6]) as a direct result of the US–Japan Cooperative Program for Development of Test Standards. The standard uses compact (CT) specimens with fatigue precracking to provide a sharp crack front.

The objective of this paper is to investigate the effect of specimen size and side grooving on the 4-K fracture toughness of types JN1 and JJ1 austenitic stainless steels, and to examine the temperature rise during dynamic crack growth. \( J_{IC} \) tests were performed with CT specimens at 4 K following JIS Z 2284. In addition to 4-K fracture toughness determinations, temperature rise near the crack tip of JJ1 specimen was measured with Au/0.07%Fe-Chromel thermocouple. The role of inclusions in the dimple rupture fracture process was also considered by careful examination of the fracture surfaces.

2. Experimental procedure

2.1. Materials and specimens

Rolled JN1 was supplied from the JAERI in the form of a 100-mm thick plate; a 50 metric ton ingot of JN1 was produced by vacuum oxygen decarburization and submerged arc remelting, then forged to a 350-mm slab; the slab was hot-rolled to the final thickness and solution-treated at 1373 K. Forged JJ1 was also supplied from the JAERI in the form of a 140-mm thick plate: a 50 metric ton ingot of JJ1 was produced by vacuum oxygen decarburization and electroslag remelting, then forged to a 350-mm slab; the slab was hot-rolled to the final thickness and solution-treated at 1373 K. The chemical compositions of the test materials are shown in Table 1. The yield strength \( \sigma_{YS} \), ultimate tensile strength \( \sigma_{TS} \), effective yield strength \( \sigma_Y = (\sigma_{YS} + \sigma_{TS})/2 \), and Young’s modulus \( E \) obtained for the test materials at 4 K are shown in Table 2. Following JIS Z 2277 [7] method, 4-K tensile properties were measured at a crosshead speed of 0.2 mm/min using cylindrical specimens (7-mm diameter, 35-mm gage length). These specimens were located at 25 and 35 mm from the top surface of rolled JN1 and forged JJ1 to the center of the specimen, respectively, and machined in the transverse orientation, such that the fracture plane orientation matched that of the CT specimens described below.

![Fig. 1. Compact specimen used in elastic–plastic fracture toughness tests.](image)

Table 1

| Material | C     | Si     | Mn     | P     | S     | Ni     | Cr     | Mo     | N     |
|----------|-------|--------|--------|-------|-------|--------|--------|--------|-------|
| JN1      | 0.018 | 0.33   | 4.10   | 0.019 | 0.002 | 15.26  | 25.20  | –      | 0.370 |
| JJ1      | 0.045 | 0.44   | 9.74   | 0.020 | 0.002 | 11.92  | 12.21  | 4.89   | 0.203 |

Table 2

| Material | \( \sigma_{YS} \) (MPa) | \( \sigma_{TS} \) (MPa) | \( \sigma_Y \) (MPa) | \( E \) (GPa) |
|----------|-------------------------|-------------------------|---------------------|--------------|
| JN1      | 1364                    | 1754                    | 1559                | 202          |
| JJ1      | 1110                    | 1574                    | 1342                | 193          |

Fig. 1 shows the CT specimen geometry. For the JN1 specimens, the specimen width was held constant \( (W = 50 \text{ mm}) \), but the specimen thickness was varied \( (B = 25, 12.5, 5, \text{ and } 2 \text{ mm, respectively}) \). The JJ1 specimens were 25- and 12.5-mm-thick with a width-to-thickness ratio \( (W/B = 2) \). These specimens had standard planar proportions as per JIS Z 2284. The CT specimens were machined in the T–L orientation, and located at 25 and 35 mm from the top surface of rolled JN1 and forged JJ1 to the center of the specimen, respectively. The specimens were fatigue pretrained at room temperature with final stress intensity factor range \( \Delta K = 30 \text{ MPa m}^{1/2} \). The precracking was continued to the original-crack-length-to-width ratio \( a_0/W = 0.6 \). After precracking, side-grooves were machined on some specimens to a net thickness \( (B_N) \) reduction of 20%. The nominal dimensions of all the specimens tested are listed in Table 3.

2.2. Testing method

A 100-kN capacity servo-hydraulic machine was used for the \( J_{IC} \) tests. Low temperature environment was achieved by immersing the load frame, specimen, and clip gage in liquid helium. These tests were performed in a fully automated procedure at a constant clip gage displacement rate, typically 0.12 mm/min. The single-specimen unloading compliance method described in JIS Z 2284 was used to obtain the fracture toughness parameters. Using a crack-length-versus-compliance correlation, the crack length \( (a) \) at each unloading was inferred and used to obtain the crack extension increment \( \Delta a = a - a_0 \) from the difference of the original crack length. The crack length...
Table 3
Dimensions of specimens

|          | Width W (mm) | Thickness B (mm) | Net thickness B_{n} (mm) |
|----------|--------------|------------------|-------------------------|
| **JN1**  |              |                  |                         |
| Plane    | 50.0         | 2.0              | 2.0                     |
|          | 50.0         | 5.0              | 5.0                     |
|          | 50.0         | 12.5             | 12.5                    |
|          | 50.0         | 25.0             | 25.0                    |
| Side-grooved | 50.0     | 12.5             | 10.0                    |
|          | 50.0         | 25.0             | 20.0                    |
| **JN1**  |              |                  |                         |
| Plane    | 25.0         | 12.5             | 12.5                    |
|          | 50.0         | 25.0             | 25.0                    |
| Side-grooved | 25.0     | 12.5             | 10.0                    |
|          | 50.0         | 25.0             | 20.0                    |

at each unloading is given by [6,8]:

\[
a = W(1.000196 - 4.06319U + 11.242U^2 - 106.043U^3 + 464.335U^4 - 650.677U^5)
\]

(1)

where

\[
U = \frac{1}{(B_C E C)^{1/2} + 1}
\]

(2)

and \( C \) is the specimen load line elastic compliance, and \( B_n = B - (B - B_N)/B \) is the effective thickness. The \( J \) value is calculated from [6]:

\[
J = \left( \frac{P}{(B N W)} \right)^{1/2} f \left( \frac{a_0}{W} \right)^2 \left( 1 - \nu^2 \right) \frac{E}{E_0} + J_{pl}
\]

(3)

where

\[
f \left( \frac{a_0}{W} \right) = \left\{ \frac{2 + \left( \frac{a_0}{W} \right)^2}{0.886 + 4.64 \left( \frac{a_0}{W} \right)^2 - 13.32 \left( \frac{a_0}{W} \right)^2 + 14.72 \left( \frac{a_0}{W} \right)^3 - 5.6 \left( \frac{a_0}{W} \right)^4} \right\}^{1/2}
\]

\[
J_{pl} = \frac{\eta A_{pl}}{B N b_0}
\]

(5)

\[
\eta = 2 + 0.522 \frac{b_0}{W}
\]

(6)

\[
b_0 = W - a_0
\]

(7)

and \( P \) is the applied load, \( \nu \) is Poisson’s ratio, \( J_{pl} \) is the plastic component of \( J \)-integral, \( A_{pl} \) is the area under load–displacement curve, and \( b_0 \) is the original uncracked ligament.

For JJ1 25-mm-thick side-grooved specimen, adiabatic heating was detected by measuring the internal temperature, \( T \), at a position of 32 mm from the load line at the specimen midthickness using Au/0.07%Fe-Chromel thermocouple embedded in the ligament along the fracture plane. Au/0.07%Fe-Chromel thermocouple was inserted through 1-mm hole. This hole was then filled with fine Cu powder.

After fracture testing, the final physical crack length \( a_{p_i} \), the distance from the load line to the final crack front, was measured with a digital microscope. The dimension \( a_0 \) was taken as the average of nine measurements \( a_{p_i} \) \((i = 1–9)\) taken at nine equally spaced points centered about the specimen centerline and extending to 0.005\( W \) from the root of the side-groove or surface of nonside-grooved specimens (plane specimens). The two near-surface measurements were averaged into one value and the result was used along with the remaining seven crack length measurements. Similarly, the final value of physical crack extension \( \Delta a_{p_i} \) was taken as the average of nine similar measurements between the original crack front and the end of stable crack growth. The fracture surfaces were also examined with scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) analysis.

3. Results and discussion

Figs. 2 and 3 show representative load–displacement curves for the JN1 and JJ1 specimens. JN1 and JJ1 are typical examples of the serrated plastic flow behaviors that accompany ductile fracture at 4 K. The steels fail at 4 K by repeated instabilities and arrests. The serrations become more pronounced as the test proceeds. The first few serrations may result from unstable plastic deformation that causes blunting, but no true crack extension. Subsequent serrations are certainly associated with both plastic flow and crack extension by ductile tearing. The load drops corresponding to the crack extension for the JJ1 specimens are more pronounced than those for the JN1 specimens.

The surface appearance of JN1 and JJ1 specimens are shown in Figs. 4 and 5. For the plane specimens, fatigue precracking always produced satisfactory crack front straightness, but quasi-static loading to fracture caused preferential crack advance at the center of specimen thickness (tunnelling). A recent analysis of the stress state in the plane specimen shows that near the crack front there exists a plane strain zone in the center region of the specimen and a plane stress zone near to the side surfaces. Consequently, onset of crack extension occurs in the center region. Side-grooves may be desirable to achieve plane strain condition and to help alleviate crack front tunnelling.
We introduce a crack aspect ratio $\alpha$ according to

$$\alpha = \frac{\Delta a_{\text{max}} - \Delta a_{\text{min}}}{B_N}$$

where $\Delta a_{\text{max}}$ and $\Delta a_{\text{min}}$ are maximum and minimum crack extensions, respectively. Table 4 lists the crack length measurements and related parameters. As defined in JIS Z 2284, the difference between the final crack extension, $\Delta a_f$, predicted by elastic compliance at the last unloading and the average physical crack extension, $\Delta a_p$, does not exceed 0.15 $\Delta a_p$, and none of the nine physical measurements, $a_p$, differ by more than 7% from the average physical crack length, $a_p$. All of the side-grooved specimens satisfied the crack extension and crack length requirements. Owing to tunnelling, the requirements cannot be satisfied in several plane specimens, and close agreement between the final physical crack extension and the compliance-predicted crack extension was lost. Fig. 6 shows the crack aspect ratio $\alpha$ versus specimen thickness. The values of $\alpha$ for the side-grooved specimens are independent of specimen net thickness. The values of $\alpha$ for the JJ1 plane specimens increase with decreasing thickness. In the JJ1 plane specimens, $\alpha$ values increase as the specimen thickness is reduced from 25 to 5 mm and then decrease for the 2 mm thickness.

Fig. 7 shows the $J$–resistance ($J$–$R$) curves for the JJ1 plane specimens. For the 2-mm-thick plane specimen, requirements for $J$–$\Delta a$ data point spacing were not satisfied. The slope of the $J$–$R$ curves for the plane specimens increases as the specimen thickness is reduced. A quantitative measure of $J_Q$ (candidate value of $J_{IC}$) is operationally defined as the point of intersection of the power law regression line and a blunting line, $J = 2\sigma_Y \Delta a$, drawn at a 0.2 mm offset. All of the specimens except the 2-mm-thick satisfied the thickness and ligament requirements for a valid plane-strain test as both the specimen thickness $B_N$ and original uncracked ligament $b_0$ exceeded 25 $J_Q = \sigma_Y$.

Table 5 presents the $J_{IC}$ test results for the JJ1 specimens. The critical $J$ measurements for the plane specimens are denoted $J_Q$ (not $J_{IC}$) because the standard requirements regarding uniform crack advance beyond the original crack front could not be satisfied. The $J_Q$ value is found to increase as specimen thickness decreases. The $J_{IC}$ value is independent of specimen thickness in the case of side-grooved specimens. The fracture surfaces of the broken specimens were examined using SEM. JN1 exhibited predominantly dimple rupture. The fracture surface at the center of the specimen showed relatively large dimples. The fracture surface near the side surface of the specimen showed fine dimples; this type fracture was observed in the plane specimens, which had high slope of the $J$–$R$ curve.

Table 6 lists the $J_{IC}$ test results for the JJ1 specimens. The $J_{IC}$ value of type JJ1 austenitic stainless steel lies within the range of 344.5–459.1 kJ/m². Examination of the fracture surfaces adjacent to precrack tip by SEM revealed that there was a high content of inclusions on the fracture surface of the 1T-S1 specimen compared with other specimens.
The inclusions were determined by EDX to be rich in Al, Si, Ca, and Ti. Traditionally, the process of dimple rupture is separated into three stages: (1) void nucleation, (2) void growth, and (3) void coalescence. The inclusions are a common site for void nucleation. In the 1T-S1 specimen, crack growth appears to occur by the linking of voids via microcracking rather than the coalescence of voids. The loss in toughness associated with the inclusions was found to agree with the trend determined between inclusion spacing and toughness in stainless steel welds [9].

Fig. 8 shows the $J-R$ curves for the JJ1 side-grooved specimens except 1T-S1. The $J_{IC}$ value is independent of specimen size over the range studied within some reasonable scatter.

In cryogenic environments the energy absorption in materials can lead to large local temperature rises due to the low specific heats of materials. Fig. 9 shows the load–displacement curve and adiabatic heating behavior for the JJ1 side-grooved specimen (1T-S2). In the initial stages of stable loading, the internal temperature, $T$, increases as nonlinear loading develops. As testing continues and serrations begin, load drops occur with increasing magnitude accompanied by higher temperature bursts. We introduce an increase in plastic component of $J$-integral $\Delta J_{pl}$ and temperature rise $\Delta T$ according to

$$\Delta J_{pl} = \left(2 + 0.522b_0/W\right)\Delta A_{pl}/B_Nb_0$$

$$\Delta T = T - 4$$

where $\Delta A_{pl}$ is the area as shown in Fig. 9. Fig. 10 shows the relationship between $\Delta T$ and $\Delta J_{pl}$ for the 1T-S2 specimen. We found excellent correlation between $\Delta T$ and $\Delta J_{pl}$. The best fit equation of data in Fig. 10 is

$$\Delta T = \beta(\Delta J_{pl})^{1/2}$$
where $\beta$ is a coefficient and is taken to be $\beta = 3.53$ for type JJ1 austenitic stainless steel.

Adiabatic heating is prominent in cryogenic tests. Material properties at extreme cryogenic temperatures can be affected by adiabatic heating which occurs whenever the rate of heat generated from plastic work exceeds the cooling capability of the cryogen. The heating during continuous loading is modest and can be

![Fig. 5. Surface appearance of JJ1 plane: (a) $B = 12.5$ mm, (c) $B = 25.0$ mm and side-grooved specimens: (b) $B_N = 10.0$ mm, (d) $B_N = 20.0$ mm.](image)

Table 4

Results of crack length measurements

| Plane | $\Delta a_l$ (mm) | $\Delta a_{p}$ (mm) | $(\Delta a_l - \Delta a_{p})/\Delta a_{p} \times 100\%$ | $\alpha$ | $(a_{a_l} - a_{a_{p}})/a_{a_{p}} \times 100\% (i = 1 \sim 9)$ |
|-------|------------------|------------------|---------------------------------|--------|---------------------------------|
| **JJ1** | | | | | |
| Plane | | | | | |
| $B = 2.0$ mm | 2.87 | 0.67 | 328.4 | 0.599 | $- 2.0 \sim 1.8$ |
| $B = 5.0$ mm | 1.98 | 1.80 | 10.0 | 0.779 | $- 16.5 \sim 8.4$ |
| $B = 12.5$ mm | 3.04 | 3.35 | $- 9.3$ | 0.544 | $- 12.7 \sim 7.2$ |
| $B = 25.0$ mm | 2.97 | 3.26 | $- 8.9$ | 0.285 | $- 15.1 \sim 5.6$ |
| Side-grooved | | | | | |
| $B_N = 10.0$ mm | 5.69 | 5.53 | 2.9 | 0.098 | $- 1.1 \sim 1.7$ |
| $B_N = 20.0$ mm | 4.58 | 4.49 | 2.0 | 0.083 | $- 1.5 \sim 3.2$ |
| **JJ1** | | | | | |
| Plane | | | | | |
| 0.5T-P1 $B = 12.5$ mm | 2.01 | 2.38 | $- 15.5$ | 0.308 | $- 15.1 \sim 5.9$ |
| 0.5T-P2 $B = 12.5$ mm | 1.89 | 2.30 | $- 17.8$ | 0.300 | $- 13.6 \sim 7.1$ |
| 1T-P1 $B = 25.0$ mm | 2.68 | 3.24 | $- 17.3$ | 0.268 | $- 11.5 \sim 8.1$ |
| 1T-P2 $B = 25.0$ mm | 1.03 | 1.37 | $- 24.8$ | 0.146 | $- 5.3 \sim 3.3$ |
| 1T-P3 $B = 25.0$ mm | 1.62 | 2.05 | $- 21.0$ | 0.199 | $- 9.7 \sim 5.3$ |
| Side-grooved | | | | | |
| 0.5T-S1 $B_N = 10.0$ mm | 3.26 | 3.60 | $- 9.4$ | 0.050 | $- 5.7 \sim 2.0$ |
| 1T-S1 $B_N = 20.0$ mm | 1.72 | 1.66 | 3.6 | 0.118 | $- 4.5 \sim 2.7$ |
| 1T-S2 $B_N = 20.0$ mm | 3.67 | 3.54 | 3.7 | 0.073 | $- 2.7 \sim 1.3$ |
| 1T-S3 $B_N = 20.0$ mm | 3.20 | 3.11 | 2.9 | 0.090 | $- 2.0 \sim 3.1$ |
practically eliminated by the appropriate selection of testing speed. But the huge temperature spikes developed during serrations cannot be avoided and their effects on fracture may be significant. This finding is incorporated in developing 4-K standard test procedures. The testing speed should be low enough to allow the specimen temperature to return to 4 K after the arrest of each serrations.

| Table 5 |
| Results of elastic–plastic fracture toughness tests for JN1 specimens ( *, JQ ) |
| B (mm) | BN (mm) | JIC or JQ (kJ/m²) |
| Plane | | |
| 5.0 | 5.0 | 348.9* |
| 12.5 | 12.5 | 300.0* |
| 25.0 | 25.0 | 297.9* |
| Side-grooved | | |
| 12.5 | 10.0 | 279.9 |
| 25.0 | 20.0 | 266.6 |

| Table 6 |
| Results of elastic–plastic fracture toughness tests for JJ1 specimens ( *, JQ ) |
| B (mm) | BN (mm) | JIC or JQ (kJ/m²) |
| Plane | | |
| 0.5T-P1 | 12.5 | 12.5 | 445.3* |
| 0.5T-P2 | 12.5 | 12.5 | 510.7* |
| 1T-P1 | 25.0 | 25.0 | 454.9* |
| 1T-P2 | 25.0 | 25.0 | 482.6* |
| 1T-P3 | 25.0 | 25.0 | 454.2* |
| Side-grooved | | |
| 0.5T-S1 | 12.5 | 10.0 | 459.1 |
| 1T-S1 | 25.0 | 20.0 | 344.5 |
| 1T-S2 | 25.0 | 20.0 | 453.4 |
| 1T-S3 | 25.0 | 20.0 | 428.6 |

practically eliminated by the appropriate selection of testing speed. But the huge temperature spikes developed during serrations cannot be avoided and their effects on fracture may be significant. This finding is incorporated in developing 4-K standard test procedures. The testing speed should be low enough to allow the specimen temperature to return to 4 K after the arrest of each serrations.
4. Conclusions

The fracture properties of types JN1 and JJ1 austenitic stainless steels were evaluated in liquid helium at 4 K. The results are summarized as follows:

1. We need the side-grooved specimens to obtain the $J_{IC}$ values. The $J_{IC}$ is independent of specimen size for side-grooved specimens.
2. Side-grooves reduce the end-of-test disparity between compliance predicted and physically measured crack extension values.
3. The presence of inclusions severely reduces fracture toughness.
4. The magnitude of heating can be explained in terms of the level of plastic deformation associated with fracture.

Acknowledgements

The authors are grateful to Dr H. Tsuji and Mr H. Nakajima of the Japan Atomic Energy Research Institute for preparing JN1 and JJ1 samples used in this study.

References

[1] Final Report of the ITER Engineering Design Activities, Proposed by the ITER Council, International Atomic Energy Agency, Vienna, July 2001.
[2] K. Ishio, H. Nakajima, Y. Nunoya, Y. Miura, T. Kawasaki, H. Tsuji, Trial fabrication of heavy section base metals and welded joints for ITER TF coil, Advances in Cryogenic Engineering 44 (1998) 73–80.
[3] H. Nakajima, K. Yoshida, S. Shimamoto, Development of new cryogenic steels for the superconducting magnets of the fusion experimental reactor, ISIJ International 30 (1990) 567–578.
[4] ASTM E 1820-01, American Society for Testing and Materials, Standard Test Method for Measurement of Fracture Toughness, 2001.
[5] ISO 12135, International Organization for Standardization, Metallic Materials—Unified Method of Test for the Determination of Quasistatic Fracture Toughness, 2002.
[6] JIS Z 2284, Japanese Standards Association, Method of Elastic–Plastic Fracture Toughness $J_{IC}$ Testing for Metallic Materials in Liquid Helium, 1998.
[7] JIS Z 2277, Japanese Standards Association, Method of Tensile Testing for Metallic Materials in Liquid Helium, 2000.
[8] A. Saxena, S.J. Hudak Jr., Review and extension of compliance information for common crack growth specimens, International Journal of Fracture 14 (1978) 453–468.
[9] C.N. McCowan, T.A. Siewert, Inclusions and fracture toughness in stainless steel welds at 4 K, Advances in Cryogenic Engineering 34 (1988) 335–342.