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# Specimen size effects on fracture toughness of JLF-1 reduced-activation ferritic steel

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## Abstract

Four different sizes of compact tension (CT) specimens of a reduced activation ferritic steel, JLF-1 steel, were fabricated and the fracture toughness was measured at room temperature by means of the unloading compliance method referring to in the ASTM E1820-99a. The $J_Q$ values obtained for the 1T–1CT and 1/2T–1CT specimens were 404 and 623 kJ/m$^2$, respectively, indicating that the $J_Q$ value increased with decreasing the specimen thickness. On the other hand, the $J_Q$ value decreased when specimens were miniaturized while maintaining the similar proportions. The $J_Q$ values for the 1/2CT and 1/4CT specimens were 371 and 321 kJ/m$^2$, respectively. Specimen size effects are interpreted in terms of an increase in the plain stress state region and plastic zone size at the crack tip in the specimen.

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## 1. Introduction

Reduced-activation ferritic (RAF) steels are the prime candidate for fusion reactor structural materials [1], and their R&D is now facing the stage of so-called 'engineering valification' toward application to DEMO reactors. The International Fusion Materials Irradiation Facility (IFMIF) is required to evaluate the material performance under a fusion relevant environment. One of the important materials performance issues is fracture toughness for which the engineering database is necessary to design a fusion blanket. The RAF steels exhibit elastic–plastic behavior that can be characterized by the $J$-integral approach. Although the fracture toughness, $J_Q$, depends on the specimen size, when the specimen thickness is large enough, it is considered to be independent of the specimen size (plane strain state). So a large size specimen is used to evaluate, although it is conservative, the fracture toughness, $J_{IC}$ [2–4].

According to the standard test method, the fracture toughness is usually evaluated using at least 6 standard compact tension (CT) specimens. Thus, the required irradiation volume for fracture toughness measurement is estimated to be 560 cc, exceeding the irradiation volume of the IFMIF region where the available displacement damage is 20 dpa/year. In order to effectively produce an IFMIF irradiation database, the reduction of the specimen volume is strongly needed without loosing data reliability by specimen miniaturization.

Therefore, it is necessary to clarify the characteristic change of the fracture toughness in miniaturized specimens, that is, the size effect, and to understand the correlation rule with standard size specimens for valid fracture toughness.

In the present paper, fracture toughness of the RAF steel (JLF-1) is evaluated by applying small specimen testing techniques to the $J_{IC}$ measurement in order to establish an appropriate evaluation method for fracture toughness with miniaturized CT specimens in anticipation of IFMIF irradiation experiments of fusion blanket structural materials.

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## 2. Experimental procedure

The material used in this study was the JLF-1LN steel (JLF-1 JOYO-heats) [1]. A steel plate of 30 mm thickness was heat-treated at 1323 K for 1 h and air-cooled (normalizing), and then tempered at 1053 K for 1 h, followed by air-cooling. Chemical compositions and tensile properties of the JLF-1LN are shown in Table 1. Four different sizes of compact tension (CT) specimens were fabricated as shown in Table 2. The geometries of 1T–1CT, 1/2CT and 1/4CT specimens have similar proportions. Prior to the fracture toughness test, a fatigue pre-crack was introduced into the specimen until the final $K$ value was 21.7, 21.4 and 20.1 MPa $\sqrt{m}$ for 1CT, 1/2CT and 1/4CT specimen, respectively. The initial value of the maximum fatigue load was 11.8, 4.90 and 0.16 kN for 1CT, 1/2CT and 1/4CT specimen, respectively. And then the specimens were side-grooved by 25% (25% SG) of their thickness with the root radius of 0.1 mm. The fracture toughness tests were carried out at room temperature according to the ASTM E1820-99a by means of the unloading compliance method [5,6].

Tensile specimens were produced in accordance with the JIS which defined the specimen gage length and diameter as 40 and 6.25 mm, respectively. The tensile tests were carried out using an INSTRON-type machine at a cross head speed of 0.1 mm/min at room temperature.

## 3. Results

The load–load line displacement curves of all the specimens are shown in Fig. 1. Even for the miniaturized CT specimens (1/2CT, 1/4CT), these curves were very smooth, and the unloading and reloading lines were very clear, suggesting the occurrence of stable crack growth during the tests. The $J$-integral and crack extension (J-R) curves of these specimens are shown in Fig. 2. The $J_Q$ values obtained for the 1T–1CT and 1/2T–1CT specimens were 422 and 620 kJ/m$^2$, respectively. The fracture toughness increased as the specimen thickness decreased. On the other hand, the fracture toughness decreased when the specimens were miniaturized while keeping the same proportions, resulting in $J_Q$ values for the 1/2CT and 1/4CT specimens that were 382 and 300 kJ/m$^2$, respectively.

Fig. 3 show the SEM images of the fracture surface after the tests. The two regions, the fatigue pre-crack and the actual crack growth, appeared to be separated by a narrow band referred to as the stretch zone. this is the interface between the fatigue pre-crack (indicated by arrows) and the area of crack growth during the test as well as crack extension resulted from blunting of the fatigue pre-crack. Each size of CT specimen showed a

Table 1
Chemical compositions and tensile properties of JLF-1 steels (wt%) (Nippon Steel Company (wt%))

| Material | C | Si | Mn | P | S | Cr | W | V | Ta | Ti | B | N | Tensile properties | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | YS (MPa) | UTS (MPa) | TE (%) |
| JLF-1 IEA-heat | 0.10 | 0.05 | 0.45 | 0.003 | 0.0002 | 8.85 | 1.99 | 0.20 | 0.080 | – | 0.0002 | 0.0231 | | | |
| JLF-1 LN | 0.098 | 0.050 | 0.50 | <0.002 | 0.0004 | 8.99 | 2.00 | 0.20 | 0.098 | <0.002 | 0.0001 | 0.0149 | 450 | 620 | 22.8 |

YS: yield stress, UTS: ultimate tensile stress, TE: tensile elongation.
Heat treatments: normalized at 1323 K for 1 h and then tempered at 1053 K for 1 h, followed by air cooling.

Table 2
Dimensions of CT specimens

| Specimen size | Width, $W$ | Thickness, $B$ | Original crack length, $a_0$ | Fatigue pre-crack length, $a$ |
|---|---|---|---|---|
| 1T–1CT | 50.8 | 24.0 | 29.60 | 2.5 |
| 1/2T–1CT | 50.8 | 12.7 | 29.60 | 2.5 |
| 1/2CT | 25.4 | 12.7 | 14.70 | 2.0 |
| 1/4CT | 12.7 | 6.35 | 7.85 | 1.5 |

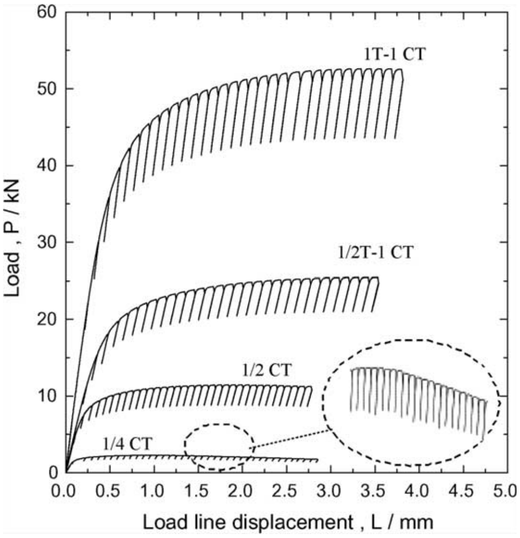

Fig. 1. Load–load line displacement curves of JLF-1 steels.

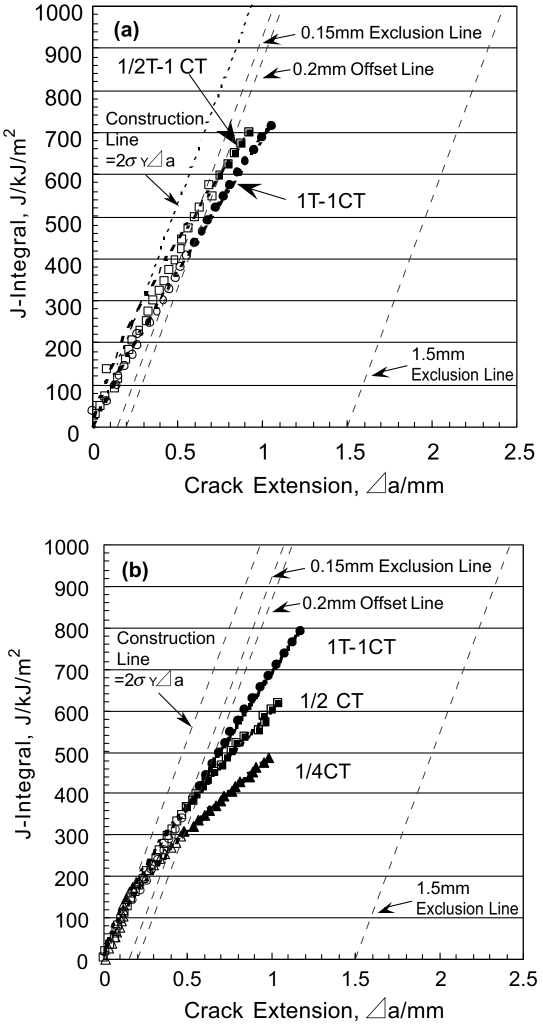

Fig. 2. $J$–$R$ curves of JLF-1.

similar type of fracture surface with standard specimens [7,8]. The successful introduction of the fatigue pre-crack, which satisfied the ASTM standard, was confirmed for miniaturized specimens such as 1/2CT and 1/4CT specimens.

Fig. 4 shows the Weibull distribution of the measured fracture toughness that is necessary for dealing with a variability in the obtained fracture data [9] such as $J_Q$. The parameter $m$ (shape parameter) is determined from the gradient of the lines. For each line, the values ranged from 12.1 to 15.2, suggesting that fracture toughness data with high reliability is obtained using the miniaturized specimens.

According to ASTM E1820-99a, the specimen thickness ($B$) or ligament length ($b_0$) requirement is described as follows:

$$B \text{ or } b_0 > 25(J_Q/\sigma_Y), \tag{1}$$

where $\sigma_Y$ is the average of the 0.2% off-set stress and the ultimate tensile strength. Only 1T–1CT specimen satisfied Eq. (1) among the four kinds of specimens. However, according to the ASTM standard, the slope of the power law regression line, $\mathrm{d}J/\mathrm{d}a$, evaluated at $\Delta a_Q$ has to be less than $\sigma_Y$, but in the case of 1T–1CT specimen, $\mathrm{d}J/\mathrm{d}a$, evaluated at $\Delta a_Q$ was more than $\sigma_Y$. From these results, it is recognized that JLF-1 steel has excellent fracture toughness. Therefore thicker CT specimens are needed to obtain valid fracture toughness

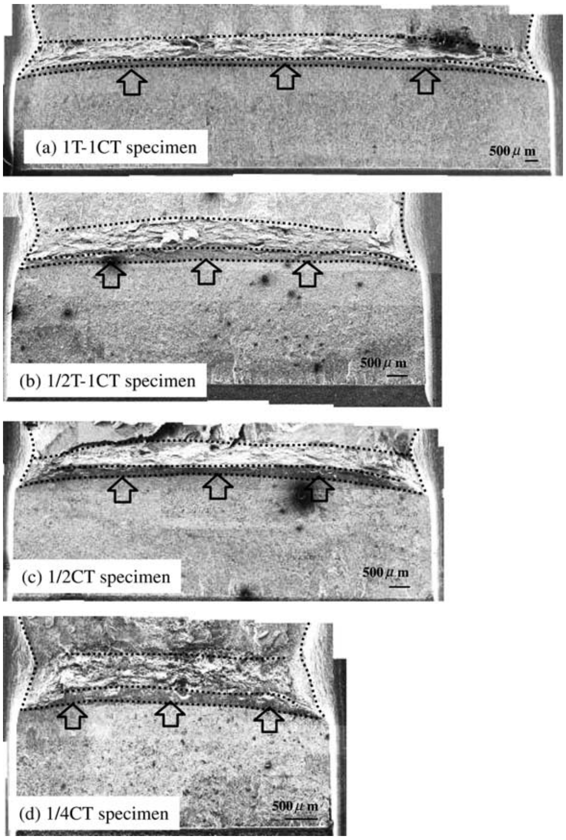

Fig. 3. Fracture surfaces of JLF-1 for CT specimens.

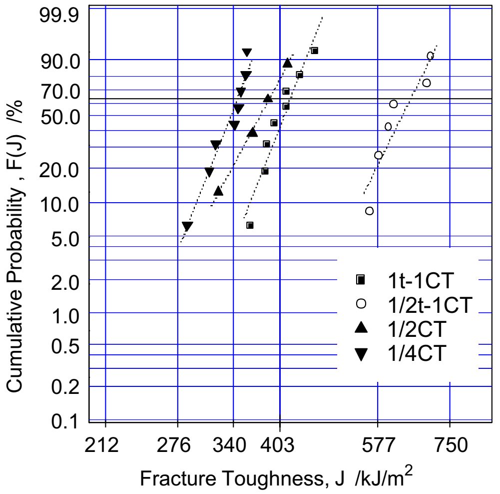

Fig. 4. Weibull plots of fracture toughness $J_Q$ obtained from the CT specimens of JLF-1, at various specimen sizes.

values for $J_{IC}$ in the unirradiated condition at room temperature.

## 4. Discussion

### 4.1. *Effect of specimen thickness on fracture toughness, $J_Q$*

The effect of specimen thickness on fracture toughness, $J_Q$, is shown in Fig. 5(a). The average $J_Q$ value obtained for the 1T–1CT and 1/2T–1CT specimens were 404 and 623 kJ/m$^2$, respectively. The fracture toughness increased as the specimen thickness decreased. Two possible explanations of the above results are as follows.

(1) It is considered that the plane stress state becomes predominant as specimen thickness decreases, and the plastic zone size at the crack tip increases near specimen side surfaces. Since the energy spent on the plastic deformation increased, the fracture toughness increased.

(2) The crack growth occurs at the weakest part of crack front (weakest-link theory). It is considered that the fracture probability increases as the specimen thickness increases, and the 1T–1CT specimen presented a low fracture toughness.

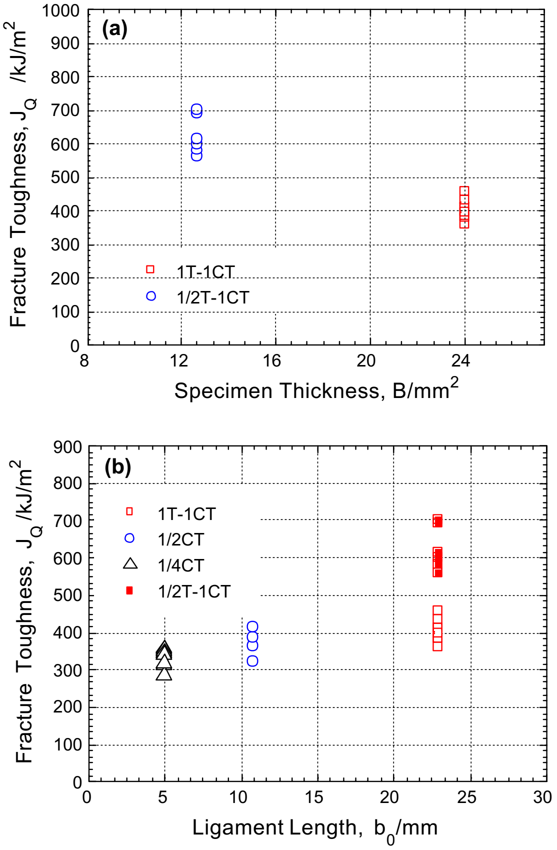

Fig. 5. Effect of specimen size on fracture toughness $J_Q$.

However, according to the data in Fig. 4, the Weibull distribution form of the 1T–1CT was similar to 1/2T–1CT. It appears that the first factor is more significant in the specimen thickness effect on the fracture toughness obtained for the two type of specimens.

### 4.2. Effect of ligament size on fracture toughness, $J_Q$

Fig. 5(b) shows the fracture toughness decreases when the specimens were miniaturized while keeping the same proportions, leading to average $J_Q$ values for the 1/2CT and 1/4CT specimens reduced to 371 and 321 kJ/m$^2$, respectively. Comparing the 1/2T–1CT and 1/2CT specimens, the fracture toughness decreases as the ligament length decreased while maintaining the same thickness.

One of the possible explanations for the results is as follows. According to the slip-line field analysis for the static loading [10], the plastic zone size at the crack tip is described by $2(J/\sigma_{ys})$ where $\sigma_{ys}$ is the yield stress of the material. The value obtained for JLF-1 is around 1.6 mm for a standard size specimen. It can be considered that almost half of the ligament length was occupied by the plastic zone in the 1/4CT specimen, while there was enough ligament length in the 1T–1CT specimen. When the specimen size becomes extremely small like 1/4CT size, the ligament size becomes too small to suppress gross yielding, resulting in flow instability and a decrease in the $J_Q$ values for the smaller specimens.

Among the obtained $J_Q$ values for the different size specimens, only the value of the 1T–1CT specimen was valid according to the valid criteria of Eq. (1) and those of other size specimens were invalid. However, the reduction of fracture toughness coupled with hardening, which will be induced by high doses of neutron irradiation, may decrease the specimen thickness that satisfies Eq. (1). An assumption that the irradiation-induced reduction of fracture toughness and irradiation hardening is 40% and 300 MPa, respectively, the minimum thickness required to obtain a valid value was estimated to be 9 mm, indicating that even after neutron irradiation, the fracture toughness obtained with using 1/4CT specimen will still be invalid.

Since the first wall thickness is estimated to be less than 5 mm for a ferritic steel–water blanket system, the obtained fracture toughness values for the first wall are always invalid before and probably after irradiation. A new validity criterion needs to be established for thin specimens to provide a valid database for fracture toughness of fusion blanket structural materials.

## 5. Conclusion

This paper deals with the fracture toughness of JLF-1. The main results are:

1. The fracture toughness, $J_Q$, of the 1T–1CT and 1/2T–1CT specimens were 404 and 623 kJ/m$^2$, respectively. The fracture toughness increased as the specimen thickness decreased.
2. The fracture toughness decreased when the specimens were miniaturized while keeping similar proportions, resulting in $J_Q$ values for the 1/2CT and 1/4CT specimens reduced to 371 and 321 kJ/m$^2$, respectively.
3. Specimen size effects are interpreted in terms of an increase in the plain stress state region and plastic zone size at the crack tip in the specimen.

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## References

[1] R. Kasada, H. Ono, H. Sakasegawa, T. Hirose, A. Kimura, A. Kohyama, Fus. Sci. Technol. 44 (2003) 145.
[2] A. Nishimura, N. Inoue, T. Muroga, J. Nucl. Mater. 258–263 (1998) 1242.
[3] M.A. Sokolov, J.P. Robertson et al., Effect of Radiation on Materials: 20th International Symposium, 2000, p. 125.
[4] H.P. Keller, D. Munz, STM STP 631 (1977) 217.
[5] Standard Test Method for Measurement of Fracture Toughness, ASTM E 1820-99a, 2000.
[6] J.A. Joyce, ASTM Manual Series: MNL27, 1996.
[7] W.J. Mills, Int. Mater. Rev. 42 (1997) 45.
[8] C.A. Griffis, Trans. ASME (1975) 278.
[9] T. Misawa, T. Adachi, M. Saito, Y. Hamaguchi, J. Nucl. Mater. 150 (1987) 194.
[10] J.R. Rice, Trans. ASME, J. Appl. Mech. (1968) 379.