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Fracture toughness of low activation ferritic steel (JLF-1) weld joint at room temperature

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Abstract

A low activation ferritic steel has been developed for a candidate of a structural material of nuclear fusion reactors. Since welding must be performed when the support structures are constructed, fracture toughness of the weld joint has to be characterized as well as the base metal in an engineering sense. In this report, 25 mm thick plates of JLF-1, which contains 9% Cr and 2% W, are butt-welded by a tungsten inert gas (TIG) procedure, and the fracture toughness of the base plate and the weld metal is investigated at room temperature using 1T and 0.5T CT specimens. The base metal reveals high fracture toughness of about 430 kJ/m^2. However, the weld metal showed unstable big pop-ins. One sample fractured in a nearly elastic condition and another sample showed a toughness of over 400 kJ/m^2.

1. Introduction

Activities to develop low activation ferritic steels for nuclear applications have been carried out under IEA international collaboration, and 8Cr–2W ferritic steel, named F82H, and 9Cr–2W ferritic steel, named JLF-1, have been fabricated in Japan [1,2]. Regarding fracture toughness, smaller size test specimens have been used frequently because of space limitations in neutron irradiation facilities and/or small plate thicknesses [3,4]. In the second heat of JLF-1, 25 and 15 mm thick plates were produced for the purpose of investigating: (1) fracture toughness using one inch thick compact tension specimen (1T CT), (2) weldability of a tungsten inert gas (TIG) welding and an electron beam welding, and (3) studies of the influence of neutron irradiation on mechanical properties.

Generally, fracture toughness has been evaluated using a full size CT (1T CT) for structural materials, and material selection in design of support structures has been performed based on a data base obtained empirically according to ASTM standards. Therefore, it will be a good contribution to characterize the fracture toughness of the low activation ferritic steel of JLF-1 using a full size CT specimen.

In this report, the tensile properties and the fracture toughness at room temperature of the JLF-1 base metal and weld joint are presented and discussed.

2. Experimental procedures

The chemical composition of the JLF-1 steel plate in wt% is Fe–0.10C–0.05Si–0.45Mn–0.003P–0.002S–0.003Al–8.85Cr–1.99W–0.20V–0.080Ta–0.0231N–0.0002B– $<$ 0.01Ni– $<$ 0.05Cu– $<$ 0.001Mo– $<$ 0.002Nb. The plate was 25 mm thick and heat-treated as follows: 1323 K/3.6 ks/air cooled (normalizing) and 1053 K/3.6 ks/air cooled (tempering). Two plates of ca 160 mm wide and ca 500 mm long were butt-joined by TIG welding. U-shape weld grooves were arranged along 500 mm edges and total weld passes were 25 [5]. After welding, a heat treatment of 1013 K/10.8 ks/furnace cooled was performed as a post weld heat treatment. The microstructures of the base metal and the weld metal are shown in Fig. 1. Both of them show tempered martensite. The grain size of the weld metal is almost same as that of the base metal and both grains are very fine as reported by Inoue et al. [5]. All specimens for tensile tests and fracture toughness tests were machined out of this welded plate.

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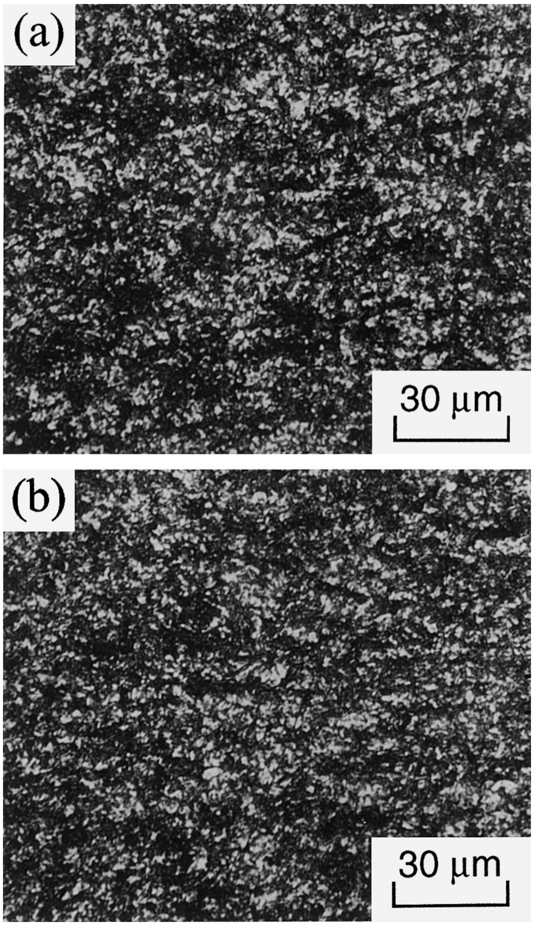


Fig. 1. Microstructures of base metal (a) and weld metal (b) (Etching solution: CH_3COOH+10%HNO_3).

The tensile test specimens have a diameter of 6.25 mm and a parallel part of 40 mm long. Four types of the tensile specimens were prepared; the first one was the base metal specimen oriented to the longitudinal direction (*L*-direction, designated as *E*), the second was the base metal specimen oriented to the transverse (*T*-direction, designated as *F*), the third was the weld joint specimen oriented to the direction transverse to the weld line (*T*-direction, designated as *G*), and the last was the weld metal specimen machined from the center of the deposit metal (designated as *H*). A cross head speed of 1.67×10^{-3} mm/s was used to measure 0.2% off-set stress and 1.67×10^{-2} mm/s was applied to measure ultimate tensile strength. To measure the 0.2% off-set stress precisely, two small extensometers were attached to the specimen symmetrically, and the load-displacement curve was recorded continuously. Elongation was measured with a gage length of 25 mm.

The configuration of the CT specimen used in this study is shown in Fig. 2. Two types of the CT specimens, i.e., 1T CT and 0.5T CT, were prepared to investigate an effect of specimen size on the fracture toughness. The fatigue pre-crack was induced and afterwards side grooves were machined to reduce the ligament section and to increase constraint on the crack front. The groove depth was about 20% of the specimen thickness and the root radius was 0.1 mm. The crack orientation was in the *L*-direction in the base metal specimen and the welding direction in the weld joint specimen. The 1T and 0.5T CT base metal specimens are designated as *I* and *K*, respectively, and the 1T and 0.5T CT weld joint specimens are designated as *J* and *L*, respectively. The cross head speed testing was 1.67×10^{-3} mm/s. The fracture toughness tests were carried out according to ASTM E813-89 [6] and a single specimen method was used. All tests were carried out at room temperature.

3. Test results and discussion

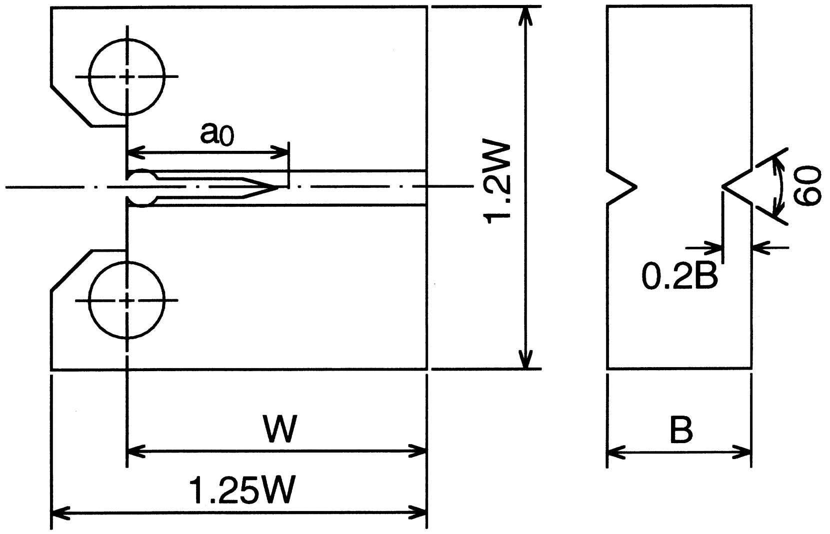
Some tensile test results are shown in Fig. 3. The base metal (F-1) shows good elongation and the weld metal (*H*-1) shows higher strength than the base metal. The weld joint (*G*-1) fractured at the base metal portion near the HAZ. So, the strength is almost same as that of the base metal and the elongation is reduced in comparison with the base metal. The tensile test results are summarized in Table 1.

Cup and cone fracture was observed in all specimens. In the base metal specimens, several sharp crevices were formed in a radial pattern. These crevices will be generated by tangential stresses during necking, and it should be noted that the deformability of the base metal will decrease under tri-axial stress condition. On the other hand, one big crevice passing through the fracture surface was observed in the weld metal specimen, and it shows inhomogeneity of the deposit metal.

Load-displacement curves of the base metal CT specimens are shown in Fig. 4. These curves are very smooth, and unloading and reloading lines are very clear. *J–R* curves of these specimens are shown in Fig. 5. The J_Q values are 419 and 431 kJ/m^2 for 1T CT and 0.5T CT, respectively. According to ASTM E813-89, the specimen thickness (B) or ligament length (b_0) requirement is described as follows:

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

where σ_{fs} is a flow stress (an average of the 0.2% off-set stress and the ultimate tensile strength). When the figures of 419 kJ/m^2 and 540 MPa are put in J_Q and σ_{fs}, respectively, 19.4 mm can be obtained for B or b_0, and it means that 0.5T CT test result does not satisfy the above requirement. In the case of 1T CT specimen, the result of 431 kJ/m^2 satisfies Eq. (1). The crack front shape requirement in ASTM E813-89 has yet to be determined as the specimens have not been opened yet.



For 1T CT specimen, W = 50 mm, B = 24 mm.
For 0.5T CT specimen, W = 24 mm, B = 12 mm.

Fig. 2. Compact tension specimen.

From these results, it is recognized that the JLF-1 steel has an excellent fracture toughness and over 20 mm thick CT specimens are needed to evaluate the valid fracture toughness in unirradiated material at room temperature.

Load-displacement curves of the weld joint CT specimens are shown in Fig. 6. Sample *J*-1 showed a big pop-in in a nearly elastic condition and the second pop-in generated a large crack extension of over 5 mm. On the other hand, sample *L*-2 was deformed to around 2.1

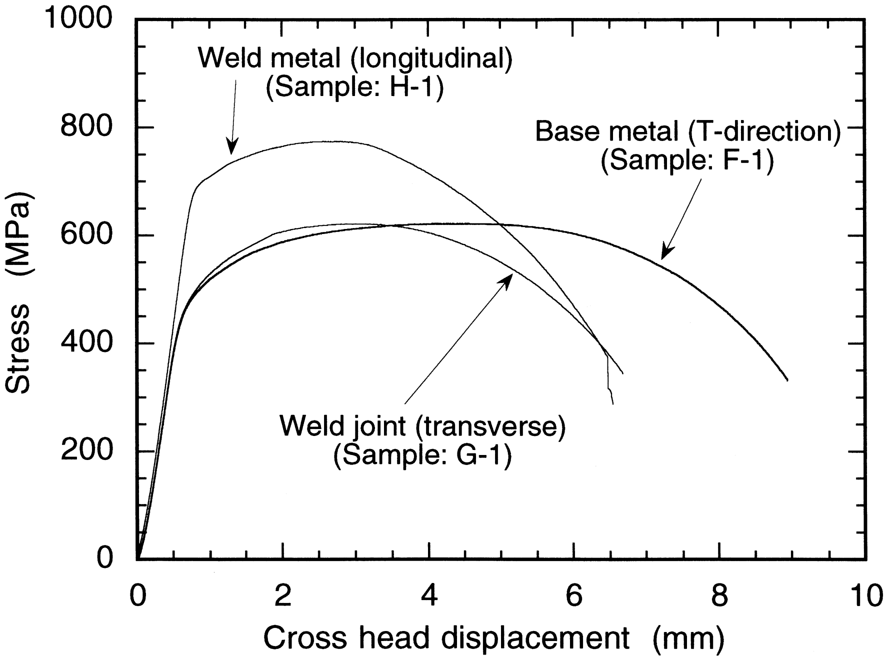


Fig. 3. Stress-cross head displacement curves of JLF-1 base metal and weld joint on tensile tests.

Table 1
Tensile test results

Spec.#	$\sigma_{0.2}$(MPa)	σ_u(MPa)	RA(%)	El.(%)	Note
E-1	454	620	77.7	28.1	Base metal (*L*-direction)
E-2	450	622	76.2	29.7	Base metal (*L*-direction)
F-1	457	623	75.4	28.5	Base metal (*T*-direction)
F-2	457	623	77.0	29.9	Base metal (*T*-direction)
G-1	–	622	75.0	–	Weld joint (fractured at base metal)
H-1	687	775	76.6	22.9	Weld metal (weld direction)

mm of a load-line displacement, then fractured in coincidence with a big pop-in. The relationship between *J* and crack extension of the weld joint specimens is shown in Fig. 7. In the sample *J*-1, the first pop-in occurred at 41 kJ/m^2, and *J* value converted from *K* value at the first pop-in load is 36 kJ/m^2. From this result, it could be concluded that the first pop-in of *J*-1 occurred in an elastic condition. In the case of sample *L*-2, it showed some plasticity and fractured at over 600 kJ/m^2. Since enough data was not obtained to make a regression curve, it is impossible to determine the J_Q, but the experimental data exists around 400 kJ/m^2 on the blunting line.

Generally speaking, the deposit metal produced by a multi-pass welding is not homogeneous and has a potential to contain a brittle phase or some kinds of weld defects. From the test results presented above, it is recognized that brittle zones or defects will be formed in the deposit metal and the fracture toughness decreases drastically when the brittle zone or the defect exists on the crack front. If such brittle zone would not be on the crack front, higher toughness of over 400 kJ/m^2 could be expected. To clarify these issues, fractographical and metallurgical investigations will be performed in near future.

4. Conclusions

This paper deals with the fracture toughness of the JLF-1 base metal and the weld joint at room temperature. The main results obtained in this study are summarized as follows:

1. The JLF-1 base metal has an excellent fracture toughness of over 400 kJ/m^2. Therefore, CT specimens with over 20 mm thick are needed to obtain the valid frac-

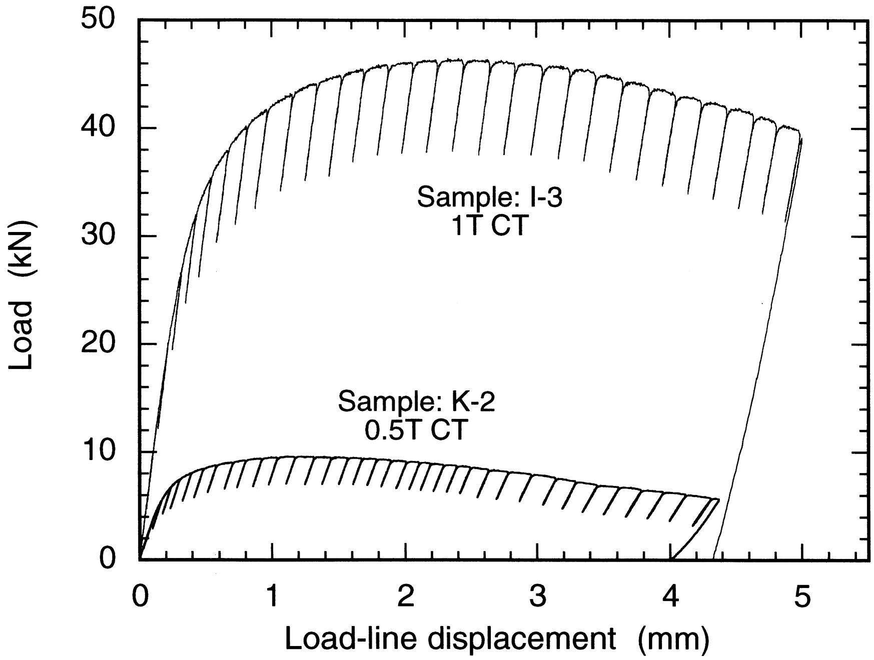


Fig. 4. Load and load-line displacement curves of CT specimens of JLF-1 base metal.

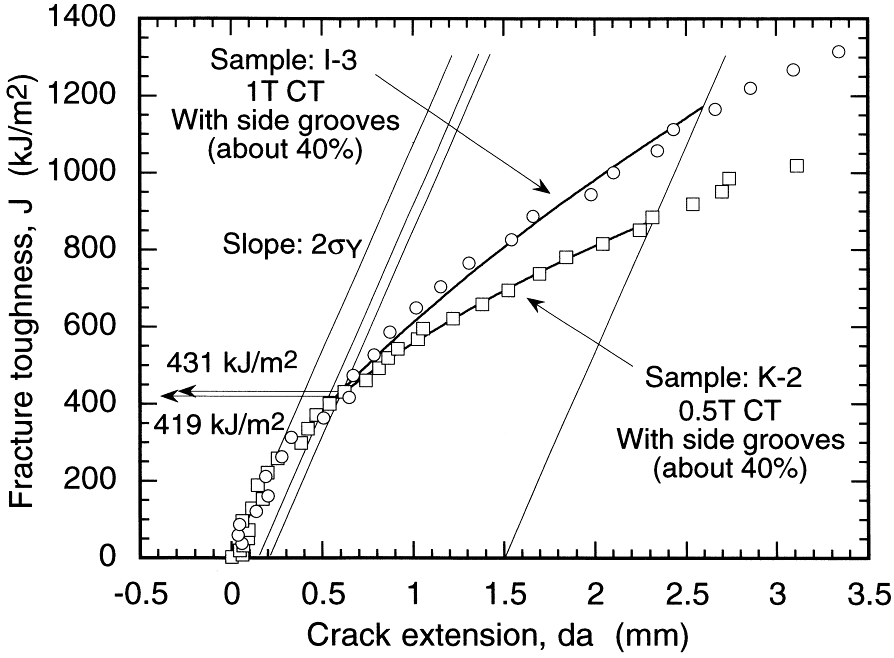


Fig. 5. *J–R* curves of JLF-1 base metal.

ture toughness according to ASTM E813-89 in unirradiated condition at room temperature.

2. The deposit metal contained brittle zones or a weld defect and it results in revealing very low fracture toughness of the weld joint. In a case of a sound deposit metal, i.e., no defects and no brittle zones, it is expected to show the fracture toughness of over 400 kJ/m^2.

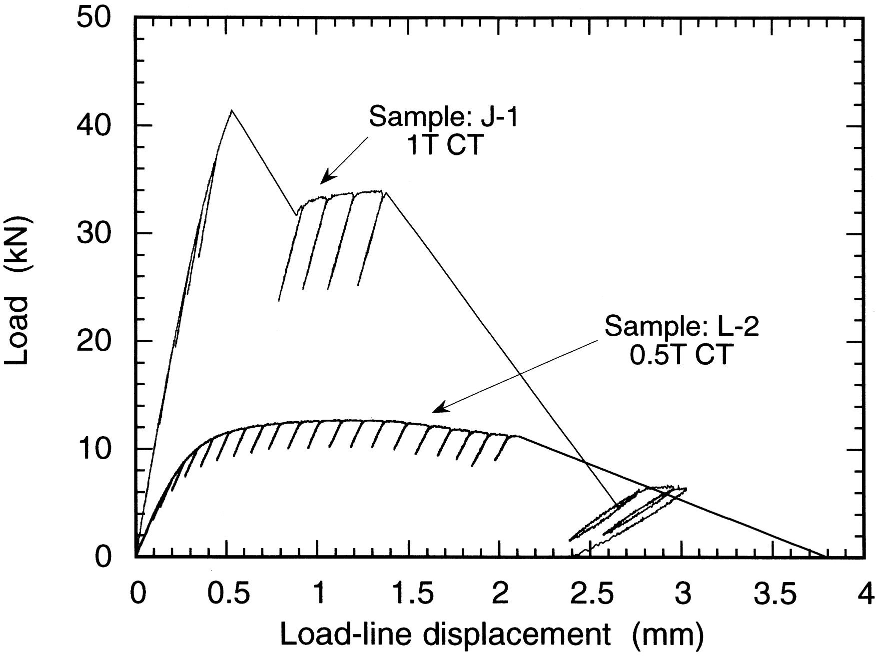


Fig. 6. Load and load-line displacement curves of CT specimens of JLF-1 weld joint.

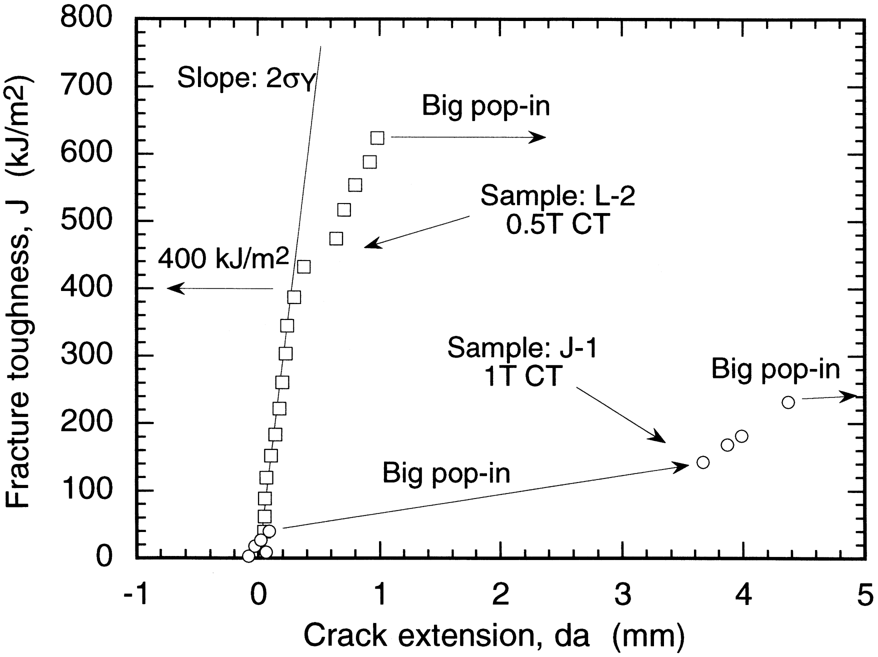


Fig. 7. J–R curves of JLF-1 weld joint.

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