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Applicability of Ultrasonic Technique for Evaluation of Elastic Plastic Fracture Toughness of High Manganese Steel at Low Temperatures

Joon-Hyun Lee*
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A study on the evaluation of elastic-plastic fracture toughness, J_{IC}, by ultrasonic technique is described for a newly developed high manganese steel at low temperature. In order to see the applicability of the ultrasonic technique based on pulse echo method at low temperature, special attention was paid to detect change point of ultrasonic echo due to the onset of stable crack growth. The J_{IC} values are evaluated by the ultrasonic method (which needs single specimen) and by stretched zone method (which needs several specimens) for compact tension(CT) specimens and three-point bend($3PB$) specimens. The temperature dependence of these J_{IC} values of the CT specimens by the ultrasonic method show almost the same values to $3PB$ specimens over the temperature range tested. The J_{IC} values of $3PB$ specimens by the stretched zone method show slightly higher values than those of the CT specimens at low temperature. The J_{IC} values evaluated by the ultrasonic method give more conservative values than those evaluated by the stretched zone method for both CT and $3PB$ specimens.

Key Words: Elastic-Plastic Fracture Toughness, J-Integral, Ultrasonic Technique, Stretched Zone Method, Pulse Echo Height, Low Temperatures

1. Introduction

The newly developed high manganese steel, 25Mn-5Cr-1Ni austentic steel, is nonmagnetic and shows high strength and toughness at low temperature(Yoshimura et al., 1982 ; Lee, J.H. et al., 1989 ; Yokobori et al., 1985). These properties ate expected to be available for LNG tank as well as for nuclear fusion reactor, MHD electric power generation and linear motor car. Since this material contains a high concentration of manganese instead of nickel, it has an added advantage in that it uses ocean resources.

Fracture toughness is one of the important material parameters, which is the measure of the cracked material's resistance to tearing and fracture. Since high manganese steel is relatively highly ductile even at low temperature, the J-integral(Rice, 1968) should be evaluated for the fracture toughness. An elastic-plastic fracture toughness value, JIC, is evaluated in conformity to the ASTM standard(E813-8) or the corresponding JSME standard(S001-1981). These method are roughly classified into two methods, that is, the multi-specimen method and the single specimen method, and the latter contains the compliance method, the ultrasonic method, the acoustic emission(AE) method and the electrical potential method.

Ultrasonic inspection, in which an ultrasonic wave is created in the material to be inspected, is a widely used NDE technique, and is very active area of research. There are several papers(Klima et al., 1976 ; Shimad et al., 1984) on evaluation of fracture toughness by ultrasonic technique using bulk wave as well as Rayleigh wave at room temperature.

* Department of Mechanical Design Engineering Materials Strength and NDE Laboratory, Research Institute of Mechanical Technology, Pusan National University, Pusan 609-735, Korea

The purpose of this paper is to discuss the applicability and its limitation of ultrasonic technique based on the pulse echo method to evaluate the J_{IC} value at low temperatures. Special attention was paid to the detection of the change point of ultrasonic echo due to the onset of stable crack growth.

2. Material and Experimental Details

2.1 Material and specimen

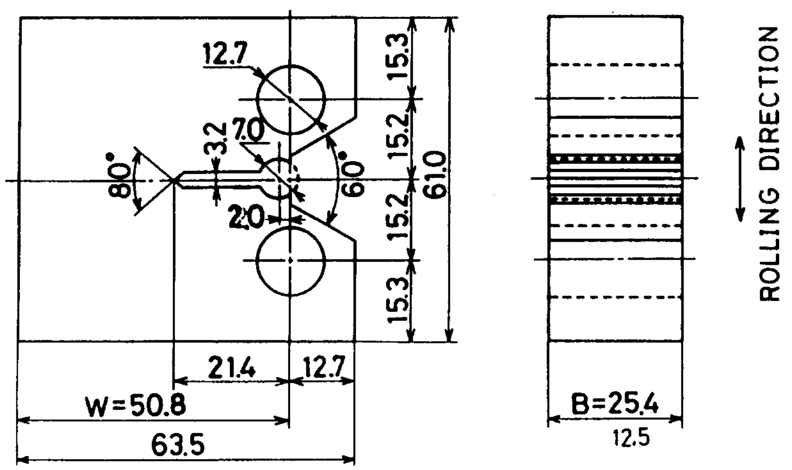
The material used was a newly developed 25Mn-5Cr-1Ni austentic steel. This steel was hot-rolled ratio 8 and solution treated by a heating at 1173 K for 60 min and subsequent quenching in water. The chemical composition and mechanical properties are shown in Tables 1 and 2, respectively. Compact tension(CT) specimens with 1 and 1/2 inch thickness and three-point bend($3PB$) specimens with a notch perpendicular to the rolling direction were prepared as shown in Fig. 1. All specimens were precracked at room temperature conforming to the ASTM standard to

Table 1 Chemical composition (weight percent)

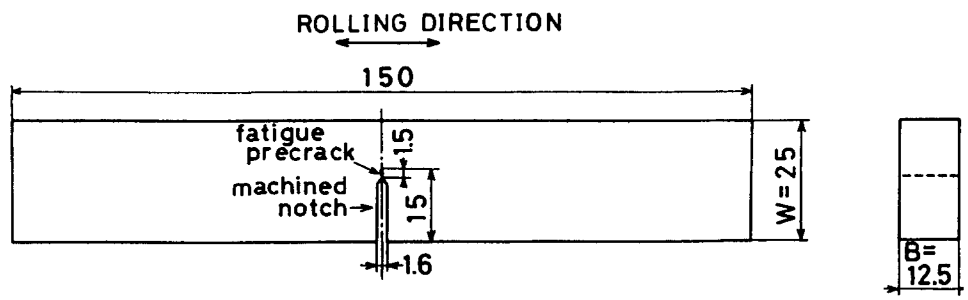
C	Si	Mn	P	S	Ni	Cr	Nb	Al
0.18	0.20	24.42	0.024	0.005	1.07	4.96	0.05	—

Table 2 Mechanical properties

Temperature	$\sigma_{0.2}$ (MPa)	σ_B (MPa)	Elongation (G.L.=50 mm)(%)	Reduction of area, (%)
R. T.	379	734	56.0	61.9
77 K	666	1200	30.0	28.7

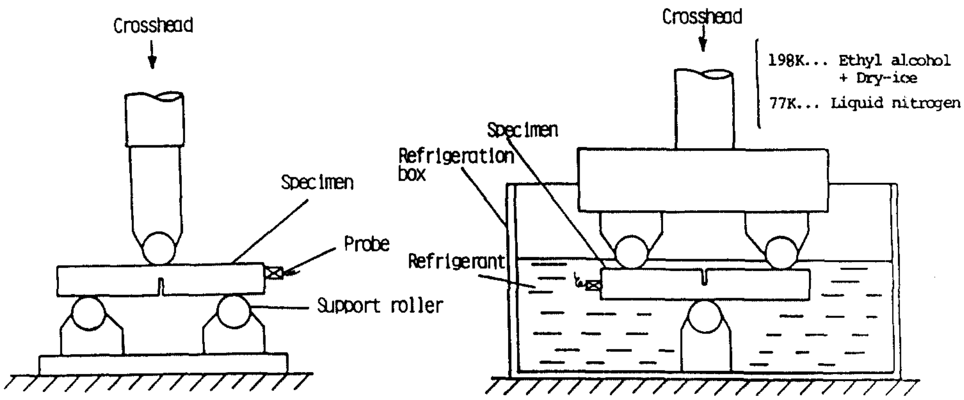


(a) Compact tension specimen



(b) Three-point bend specimen

Fig. 1 Dimensions of specimen



(a) Room temperature (b) Low temperatures

Fig. 2 Experimental set up for 3PB specimen

make the ratio of a crack length to the width, a/W, 0.6.

2.2 Experimental procedure

In order to evaluate the fracture toughness J_{IC} of $3PB$ specimen, a special apparatus shown in Fig. 2 was used. In this figure, Fig.' 2(a) shows the usual $3PB$ test at room temperature and Fig. 2(b) shows the lower temperature in the case of 199 K and 77 K. At lower temperatures, a specimen was immersed in a cooking tank filled with a refrigerant as shown in Fig. 2(b). The refrigerants were a mixture of ethyl alcohol and dry-ice for 199 K and liquid nitrogen for 77 K. For CT specimen, a servo hydraulic testing machine with a 98 KN capacity was used.

The temperature of CT specimen was measured by copper-constant thermocouple attached to each specimen ; temperature fluctuation was kept within 2 K at each temperature level in a cooling box mounted on the testing machine. The cooling box fad a coiled copper pipe surrounding the specimen ; the flow of liquid nitrogen in the pipe was regulated by controlling the delivery of a plunger pump. All of the specimens were kept in the cooling box for 20 min before testing.

2.3 Ultrasonic technique

The single specimen method has practical merit because it uses only one specimen and can save experimental cost and time. However, on the other hand, it needs some unique ideas in a special environment, such as a low temperature, to equip a measuring instrument. In this study, the ultrasonic method using a commercial ultrasonic flaw detector was employed. A probe of detector was fitted by using a setting-jig as shown in Fig. 3, so that incident pulses constantly kept in good touching condition. Before each testing at both room temperature and low temperatures, the echo pulse height was calibrated to get a reliable echo signal with relatively high gain by adjusting screw bolt on a setting-jig. A block-diagram of the test system is shown Fig. 4. The conventional straight beam probe (diameter : 10mm, center frequency : 5 MHz, characteristics bandwidth : 60%) which can send and receive ultrasonic pulses was fitted on the top surface of the specimen. Vaselinum album and low temperature coating agent C-5

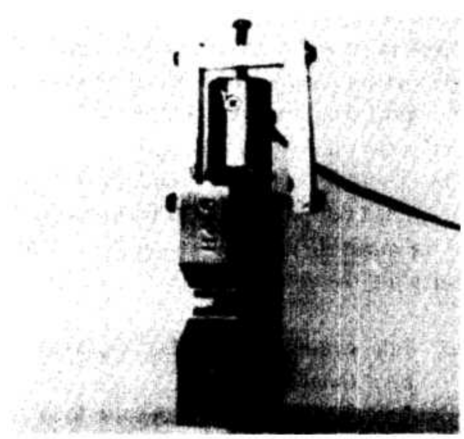


Fig. 3 Send/receive ultrasonic probe and setting jig

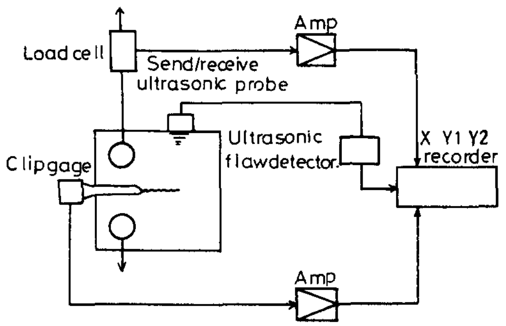


Fig. 4 Blockdiagram of ultrasonic pulse echo method for elastic-plastic fracture toughness evaluation

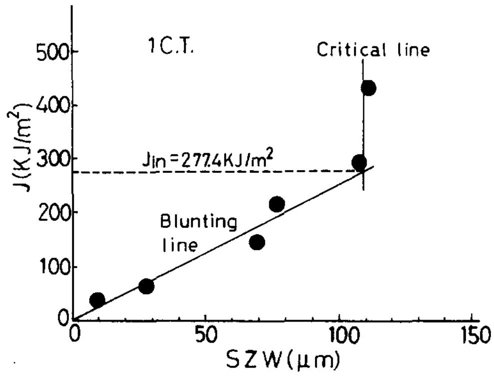
were used to improve the transmission of pulse between the probe and the specimen. The load, P, versus displacement, δ, curve and echo pulse height, E, were measured simultaneously. However, the variation of echo pulse height depended on both the testing temperature and the material strongly. therefore the correspondence of an inflection point on E-δ curve to the beginning of the stable crack growth was confirmed by simultaneous observation at a crack tip using a traveling microscope.

2.4 Stretched zone method

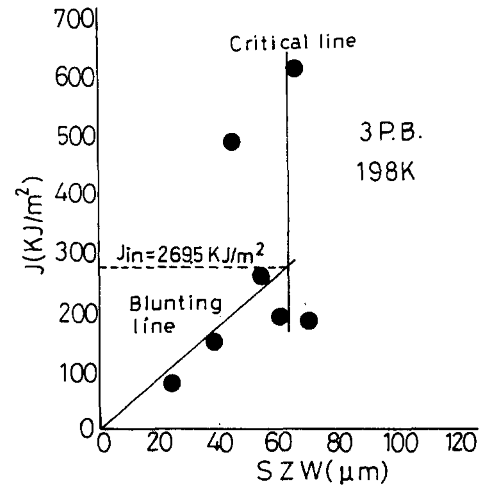
Stretched zone method is one of the typical multi-specimen method recommended by JSME standard the elastic plastic fracture toughens. In this study, the loading rate was $\dot{\delta}$ =0.25 mm/min and the load versus displacement, P-δ, diagram was recorded by X-Y plotter. After a monotonic loading until the stable growth of the precrack, CT specimen and a 3PB specimen were unloaded, respectively and were fractured under alternating loading. The stretched zone width(SZW) and critical stetched zone width($SZWc$) were measured by using a scanning electron microscope (SEM) at three points on the fractured surfaces. And the mean SZW value was obtained and used to calculate the J_{IC}.

2.5 The evaluation of elastic-plastic fracture toughness value

J-integral was calculated from the load versus displacement curve using the following



(a) 1 C.T. specimen



(b) 3 P.B. specimen

Fig. 5 Typical examples of stretched zone method for J_{IC}

formula(Merkle et al., 1974).

$$J=\frac{2b_0A}{B}\left(\frac{1+\beta}{1+\beta^2}\right) \tag{1}$$

where

$$\beta=[(2a^*/b_0)^2+2(2a^*/b_0)+2]^{1/2}-(2a^*/b_0+1). \tag{2}$$

A is the area under the P-δ curve, B is a specimen thickness, a^* is a crack length and b_0 is the uncracked ligament length.

In the SZ method, J_{IC} was evaluated from the intersection point of a blunting line and of a critical line as shown in Fig. 5. The former line was drawn through several points on a diagram of J values versus SZW in which the J value was obtained by Eq. (1). A critical line was drawn for the $SZWc$, which was measured on the surface after the fracture. And according to the JSME standard which corresponds to ASTM test method for J_{IC}, the following condition must be satisfied;

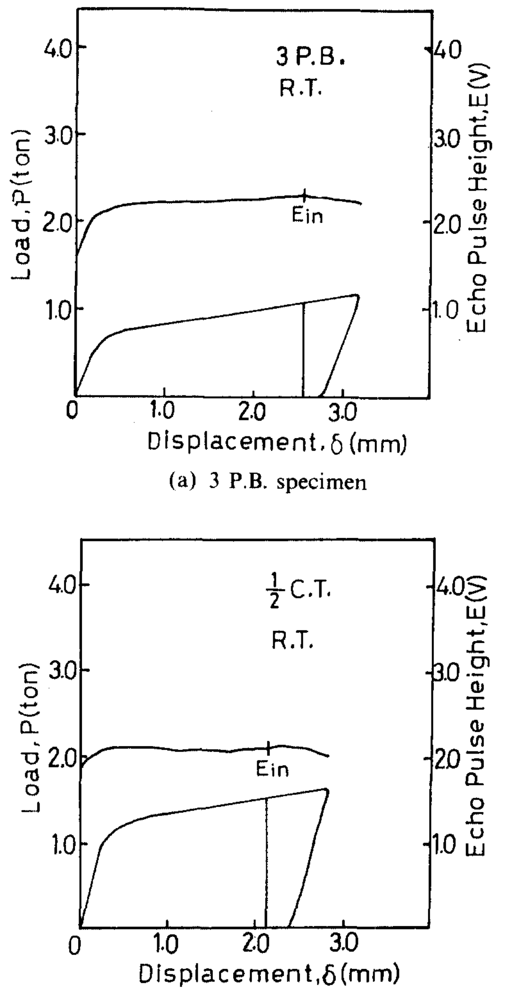
$$B \geq 25 J_{in} / \sigma_{fs} \quad (3)$$

where, J_{in} is the J-integral when a crack starts to grow, σ_{fs} is an effective yielding point and is the tensile strength, when Eq. (3) is satisfied, J_{in} corresponding to J_{IC}.

3. Experimental Results and Discussion

3.1 The ultrasonic echo pulse height

Typical examples of the record of ultrasonic echo pulse during a test for CT and $3PB$ specimens both at room temperature and at 77 K are shown in Figs. 6 and 7, respectively. It is shown from in Figs. 6 and 7 that echo pulse height, E, increases at the beginning of loading due to the increase of amount in ultrasonic beam reflected from the corresponding crack surfaces and becomes nearly constant for a short time, and then E shows another small increase. According to the simultaneous observation of the crack tip behavior by a traveling microscope it was confirmed that this secondary increase on curve corresponding to the onset of stable crack growth.



(a) 3 P.B. specimen

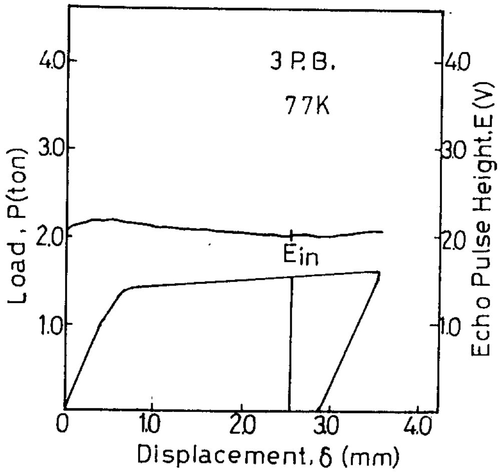
(b) 1/2 C.T. specimen

Fig. 6 Typical examples of P-δ and E-δ curve for at 297 K

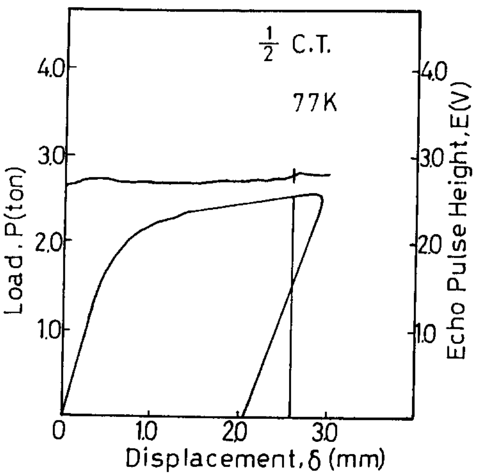
3.2 Comparision of J_{IC} values obtained by different ways

The temperature dependence of fracture toughness of high manganese steel at low temperature has already been reported(Maekawa et al.,1987) and also compares with properties SUS 304 steel.

Figure 8 shows the temperature dependence of J_{IC}, which was evaluated by the SZ method. All these J_{IC} values satisfied Eq. (2). In Fig. 8, values were almost the same for the CT and $3PB$ specimens at room temparature. But, J_{IC} values of the $3PB$ specimens seem to be a little higher than those of the CT specimens at low temperature, although there was some scatter at 99 K. This difference might be caused by the error of displacement due to local deflection of the $3PB$ specimen and the supporting roller shown in Fig. 2. Figure 9 shows the value obtained in terms of ultrasonic method is lower than that evaluated by the SZ method. Figure 10 shows the J_{IC} values evaluated by the SZ method and the ultrasonic method at several temperature levels. In the case of the CT specimen, J_{IC} values evaluated by the ultrasonic method shows good agreement with J_{IC} values evaluated by the SZ method. And the influence of specimen thickness on J_{IC} values was not observed for $1CT$ and $1/2CT$ specimens. In



(a) 3 P.B. specimen



(b) 1/2 C.T. specimen

Fig. 7 Typical examples of P-δ and E-δ curve for 77 K

case of the $3PB$ specimens, J_{IC} values were almost the same as those of the CT specimens at 288 K, but J_{IC} values evaluated by the SZ method were higher than those values evaluated by the ultrasonic method at low temperature. According to these results, it can be said that J_{IC} values evaluated by the ultrasonic method give more conservative values than those evaluated by the SZ method. Then, J_{IC} evaluation in terms of the ultrasonic method at low temperature is simple, useful and more reliable compares to the SZ method for application in industrial eniggering.

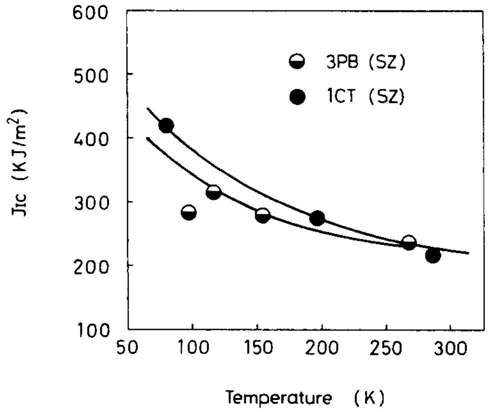


Fig. 8 J_{IC} values evaluated by S.Z. method

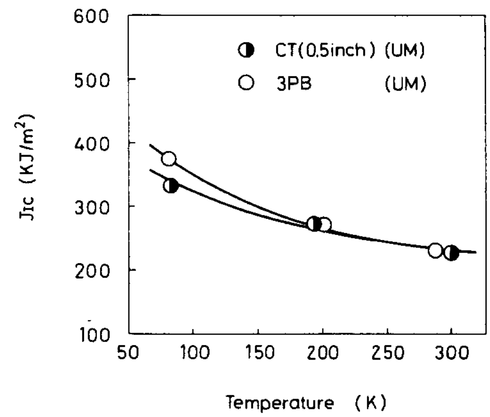


Fig. 9 J_{IC} values evaluated by ultrasonic method

3.3 Limitation of application ultrasonic method and the remaining problem

As shown in Figs. 6 and 7, the amplitude of echo variation at low temperature as very small compared with that at room temperature, specially at 77 K. It is obviously in this study that the amplitude of echo variation is very sensitive to the matching couplant between the problem and the specimen. It is thus pointed out that the selection of suitable matching couplant is one of the most important factors the successful application of ultrasonic technique at low temperature. It is also mentioned that whether this method is available with high precision or not at lower temperatures than 77 K is a very important problem remains for the future.

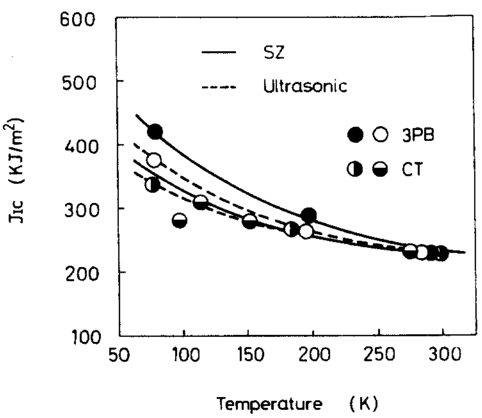


Fig. 10 Comparison of J_{IC} values evaluated by both S.Z. and ultrasonic methods

4. Conclusions

Elastic-plastic fracture toughness value was evaluated for a high manganese steel at low temperature by the ultrasonic and the *SZ* method using *CT* and 3*PB* specimens to establish the applicability of the ultrasonic method at low temperatures. The results obtained are summarized as follows.

(1) It is confirmed that ultrasonic method based on the conventional pulse echo method is simple and useful technique to evaluate elastic-plastic fracture toughness for both *CT* and 3*PB* specimens even at low temperature. However it is found that the application of this method was effective up to 77 K at low temperatures.

(2) The J_{IC} values of *CT* specimens evaluated by the ultrasonic method show almost the same values as those of 3*PB* specimens over the temperature range tested, but the J_{IC} values of 3*PB* specimens obtained by the *SZ* method show slightly higher than those of *CT* specimens at lower temperature

(3) Ultrasonic method gives slightly conservative J_{IC} values than those evaluated by the *SZ* method for both *CT* and 3*PB* specimens.

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