Dynamic Fracture Toughness and Evaluation of Fracture in a Ferritic Nodular Cast Iron for Casks

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INTRODUCTION

From the viewpoint of economy, the nuclear spent fuel shipping or intermediate storage casks of ferritic nodular cast iron have attracted particular attention and have been developed. According to the IAEA regulations, type B(U) casks shall be designed for ambient temperature range from -40 to 38°C. In addition, the structural integrity must be ensured against impact loading for a nine meter drop of casks. Unlike austenitic stainless steels, ferritic steels such as carbon steels and ferritic nodular cast irons are subject to inherent embrittlement at low temperature. Ductile-brittle transition temperature increases with increasing loading rate. Therefore, for maintaining the structural integrity of casks made of these ferritic steels, brittle or unstable fracture is an important consideration. It is reasonable to apply fracture mechanics analysis for the evaluation of fracture, and because of high loading rate the evaluation on the basis of dynamic fracture toughness is necessary.

Toughness of ferritic nodular cast irons is low in comparison with austenitic stainless steels or carbon steels because of the large amount of graphite. Therefore, as to this material, it is necessary to ensure the sufficient toughness in the ductile fracture region (upper shelf region) to prevent ductile and unstable fracture and to clarify the effect of loading rate on brittle fracture.

The objective of this study is to characterize the behavior of dynamic fracture toughness of a ferritic nodular cast iron and to evaluate this material as a material for casks.

EXPERIMENTAL METHOD

Samples were obtained from a thick-walled cylindrical casting of 500 mm in thickness. The chemical composition by weight percent was 3.56% C, 2.04% Si, and 0.15% Mn, 0.03% P, 0.001% S. Yield strength, tensile strength, and elongation were 237 MPa, 362 MPa, and 20 %, respectively. Mean graphite diameter on a test plane was in the range of 39 to 51 µm. Degree of spheroidization was 98 %. Grain size number ranged 4.7 to 5.6.

Static and dynamic elastic-plastic fracture toughness, J_{IC} and J_{Id}, respectively, were measured at temperatures below room temperature.
A drop-weight type (Yasunaka et al.1991), an electrohydraulic type and an Instron tensile testing machine were used. In the case of the drop-weight type machine, the block diagram of the measuring system is shown in Fig.1. The specimens were fatigue precracked

compact tension specimens of 25 mm in thickness as shown in Fig.2. The specimens were cooled in a cooling box in which liquid nitrogen was sprayed. An electro-optical displacement meter or a clip gage was used to measure crack opening displacement. An ultrasonic method was applied to detect the onset of crack propagation in the mid-thickness portion of specimens (Yasunaka et al. 1985).

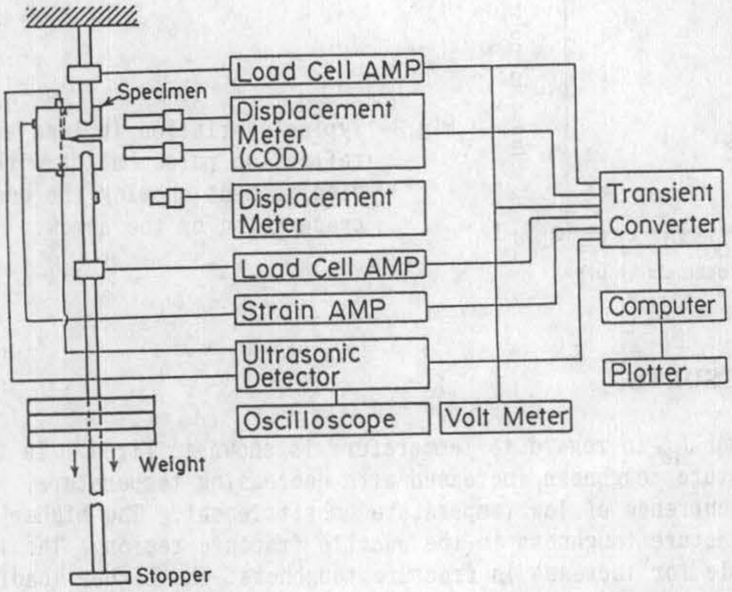

Fig.1 Block diagram of the measuring system of fracture toughness by the use of a drop-weight type tensile machine.

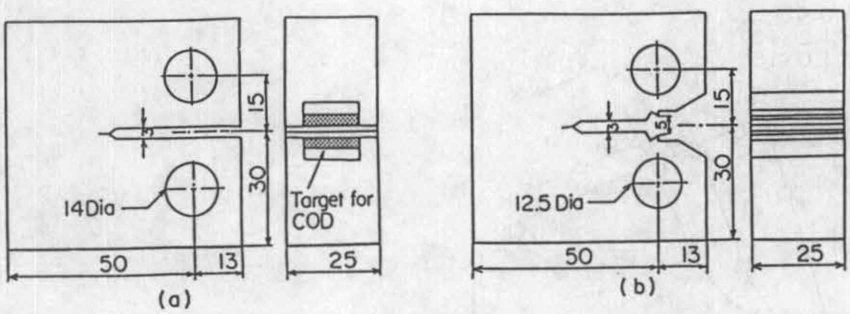

Fig.2 Configurations of the compact tension specimens for dynamic test (a) and static test (b), dimensions in mm.

Fig.3 shows a typical variation in ultrasonic pulse height and the arrow shows the onset of crack propagation in a dynamic fracture toughness test.

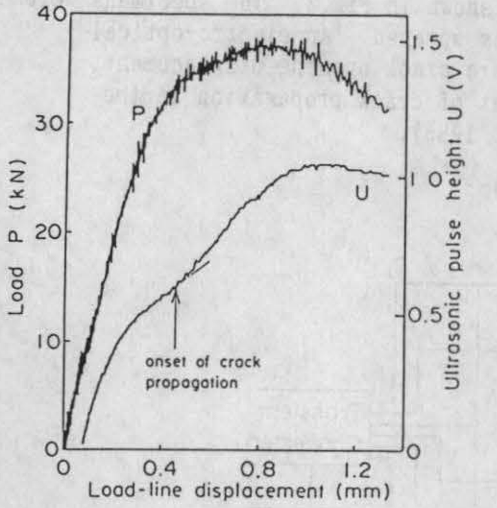

Fig.3 Typical variation in load and ultrasonic reflection pulse height with load line displacement showing the onset of crack propagation by the arrow.

EXPERIMENTAL RESULTS

The behavior of J_{IC} and J_{Id} in regard to temperature is shown in Fig.4. In the ductile fracture region, fracture toughness increased with decreasing temperature. However, it decreased with the occurrence of low temperature embrittlement. The higher loading rate led to increase in fracture toughness in the ductile fracture region. The increase in strength is responsible for increase in fracture toughness. The higher loading rate, of course, resulted in increase in ductile-brittle transition temperature.

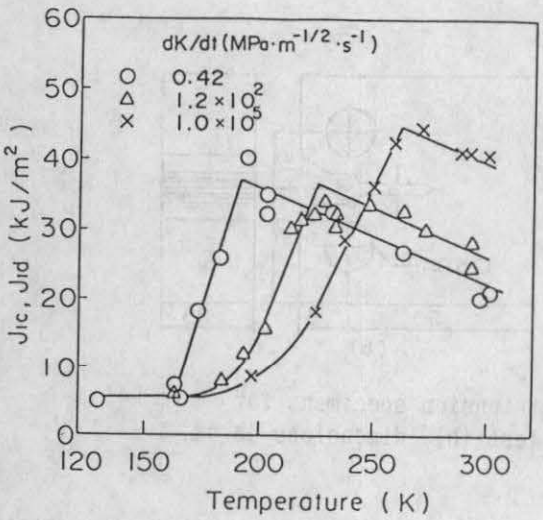

Fig.4 Variation in fracture toughness with temperature as a function of stress intensity rate.

Ductile-brittle transition temperature was linearly related to the logarithm of stress intensity rate as shown in Fig.5.
The decrease in fracture toughness in the ductile-brittle transition range was due to the occurrence of cleavage fracture. Fig.6 shows that fracture toughness is related to percent cleavage fracture.

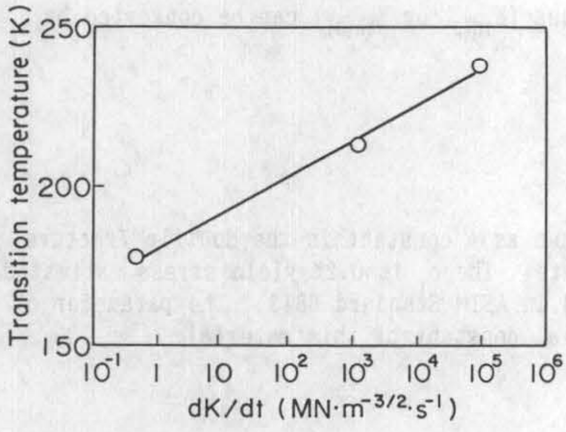

Fig.5 Relationship between ductile-brittle transition temperature and stress intensity rate.

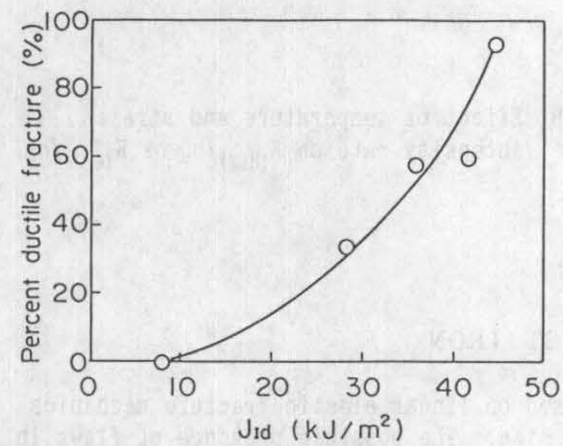

Fig.6 Relationship between J_{Id} and fraction of ductile fracture surface.

Authors have reported that the static fracture toughness J_{IC} increases with increasing graphite nodule spacing as shown in Fig.7 (Nakano and Yasunaka 1992). However, the effect of graphite nodule spacing on dynamic fracture toughness J_{Id} became small and could not be made clear in this study.

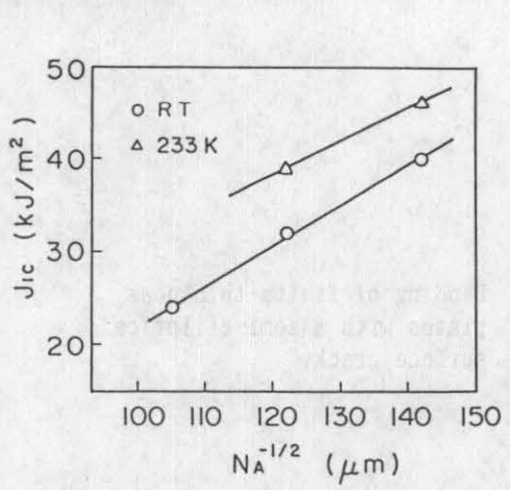

Fig.7 Effect of internodule spacing parameter $N_A^{-1/2}$ on J_{IC} at room temperature and 233 K. N_A is graphite nodule number per mm^2.

Static or dynamic plain strain fracture toughness ($K_{IC(J)}$ or $K_{Id(J)}$) can be converted by the following equation:

$$K = \{EJ/(1-\nu^2)\}^{1/2}$$

where E is the Young's modulus

ν is the Poisson's ratio

Fig.8 shows that $K_{Id(J)}/\sigma_Y$ or $K_{IC(J)}/\sigma_Y$ can be taken as a constant in the ductile fracture region regardless of temperature and loading rate. The σ_Y is 0.2% yield stress estimated by the equation of nominal limit load described in ASTM Standard E813. The parameter of $K_{Id(J)}/\sigma_Y$ or $K_{IC(J)}/\sigma_Y$ can be regarded as a material constant of this material.

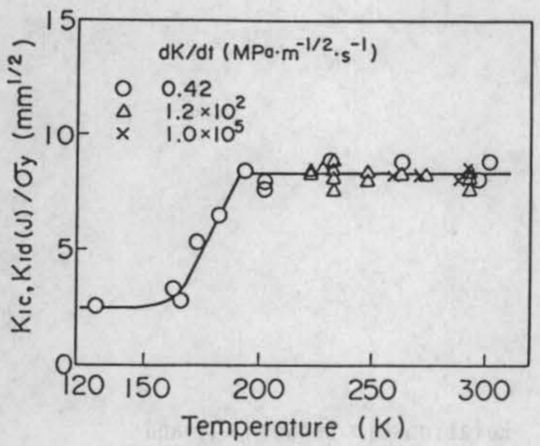

Fig.8 Effect of temperature and stress intensity rate on $K_{Id(J)}/\sigma_Y$ or $K_{IC(J)}/\sigma_Y$.

EVALUATION OF FERRITIC NODULAR CAST IRON

In order to evaluate this material, analysis based on linear elastic fracture mechanics is employed to limit the maximum allowable flaw size. The possible presence of flaws in the material must be considered. It is assumed that a semi-elliptical surface crack of length 2a and depth b exists at the mid-span on the outer surface of a cask, and the cask is subject to a side drop. This condition for the cask may be simulated by bending a plate which has such a surface crack normal to the plate surface as shown in Fig.9. At point A, the stress intensity factor increases up to a maximum value.

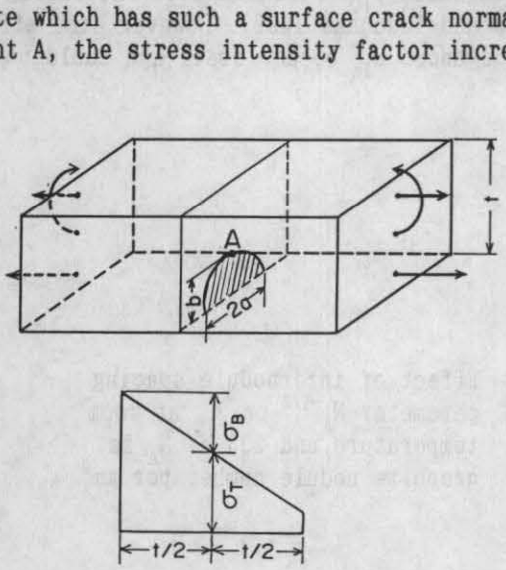

Fig.9 Bending of finite-thickness plates with a semi-elliptical surface crack.

There are many papers which give the calculation of the stress intensity factor in such a case. According to Isida et al.1984, the stress intensity factor at point A is represented by the following equation:

$$K = M(b/a, b/t)\cdot\sigma\cdot(\pi b)^{1/2}$$

where $M(b/a, b/t)$ is the correction factor

σ is the applied stress (σ_T=0 for pure bending, σ_B=0 for uniform tension)

Here b/a and t are assumed to be 1/4 and 400 mm, respectively.
In the ductile fracture region of this material, $K_{Id(J)}/\sigma_Y$ is a constant as mentioned before. Next equation is deduced:

$$\sigma/\sigma_Y = \{K_{Id(J)}/\sigma_Y\}/\{M(b/a, b/t)\cdot(\pi b)^{1/2}\}.$$

The shell of casks is deformed by the stress of mixed mode between pure bending and uniform tension.

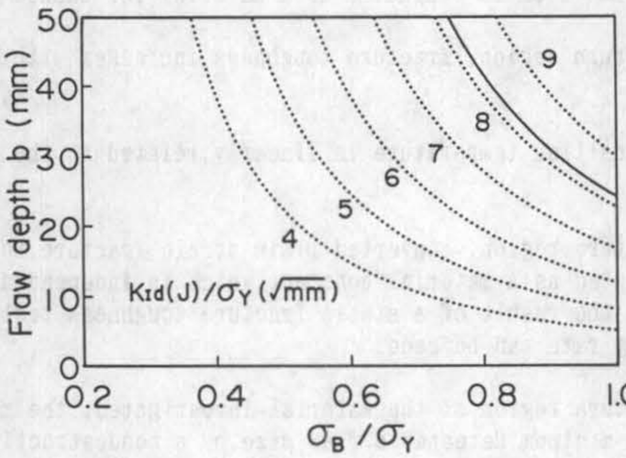

Fig.10 Relationship between critical surface flaw depth and σ_B/σ_Y in the case of ductile fracture as a function of $K_{Id(J)}/\sigma_Y$, pure bending.

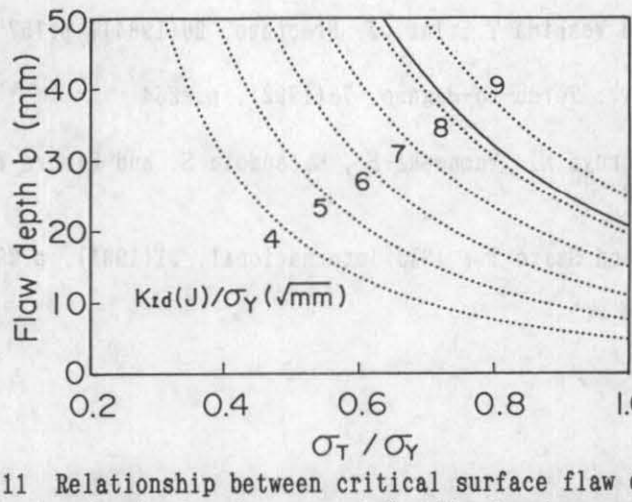

Fig.11 Relationship between critical surface flaw depth and σ_T/σ_Y in the case of ductile fracture as a function of $K_{Id(J)}/\sigma_Y$, uniform tension.

Fig.10 shows the relationship between σ_B/σ_Y and critical flaw depth b under pure bending. A solid line in the figure shows the curve for the material investigated. On the other hand, Fig.11 shows the similar relation under uniform tension. In this case, the most conservative evaluation can be made.

Considering the flaw depth which can be detected by a nondestructive inspection, ferritic nodular cast iron can be applicable to the material for casks even if applied stress is a yield level of stress. The lowest temperature of ductile fracture is dependent on the loading rate. For the more accurate prediction of fracture, it is necessary to estimate and ensure the applied stress level which depends on the effectiveness of impact limiters of casks.

CONCLUSIONS

The effect of loading rate and temperature on fracture toughness of a ferritic nodular cast iron obtained from a thick-walled cylindrical casting has been investigated. Based upon this result, the cast iron is evaluated as a material for casks.

(1) In the ductile fracture region, fracture toughness increases with increase in loading rate.

(2) Ductile-brittle transition temperature is linearly related to the logarithm of stress intensity rate.

(3) In the ductile fracture region, converted plain strain fracture toughness divided by yield stress can be adopted as a material constant which is independent of loading rate and temperature. From the result of a static fracture toughness test, the evaluation of fracture in high loading rate can be made.

(4) In the ductile fracture region of the material investigated, the maximum allowable flaw depth exceeded the minimum detectable flaw size by a nondestructive inspection. Ferritic nodular cast iron can be used as a material for casks in the ductile fracture region at least.

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