Determination of Dynamic Fracture Toughness of Nuclear Pressure Vessel Steel Using Electromagnetic Force

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Abstract

This paper is concerned with the application of the electromagnetic force to the determination of the dynamic fracture toughness of materials.

Using the electric potential and the J-R curve methods to detect the crack initiation point in the experiment, together with the finite element method to calculate the extended J-integral with the effects of the electromagnetic and the inertia forces, the dynamic fracture toughness values of the nuclear pressure vessel steel A508 class 3 are evaluated in the broad temperature range from lower to upper shelves.

The strain distribution near the crack tip in the dynamic process of fracture is also obtained by applying a computer picture processing.

1. Introduction

Various mechanical impact loading methods, e.g. the instrumented charpy test, have been employed to evaluate the dynamic fracture toughness of engineering materials [1,2]. However, such mechanical impact tests often lead to eroneous toughness values, especially in higher loading rate condition. One reason of this is due to the fact that the higher mode oscillation of specimen owing to the inertia effects gives a difficulty to accurately estimate the fracture toughness value [1]. The experimental hardness to detect the dynamic crack initiation time, especially for ductile fracture with stable crack growth, is another reason for inaccurate dynamic fracture toughness data [2].

This paper presents a new dynamic fracture testing method with the electromagnetic force [3-5]. Employed is an edge-cracked specimen as shown in Figure 1, which carries a transient electric current $\vec{I}$ and is simply supported in a steady magnetic field $\vec{B}$. As a result of their interaction, the dynamic electromagnetic force, the so-called Lorentz force, occurs in the whole body of the specimen, which is then deformed to fracture.

To show the effectiveness of the proposed method, the dynamic fracture toughness values of the nuclear pressure vessel steel A508 class 3 are evaluated at a stress intensity factor rate $\dot{K}$ near $1\times10^5 MN/m^{3/2}sec$ in broad temperature range from lower to upper shelves.

The crack tip behavior, say the strain distribution near the crack tip, during the dynamic fracture event is also investigated by using the computer picture processing [6].

2. Numerical Analyses

The two-dimensional electric current distribution in the specimen is first calculated to evaluate the electromagnetic force acting in the specimen. Following this, the two-dimensional dynamic and elastic-plastic analysis based on the J_2 flow theory is performed with the dynamic J-integral including the effects of the electromagnetic force and the inertia one, which can be written as follows.

$$J_{dyn} = \int_{\Gamma} \left(W n_1 - T_i \frac{\partial u_i}{\partial X_1} \right) d\Gamma + \int_{A} \left\{ \rho \ddot{u}_i - (\vec{I} \times \vec{B})_i \right\} \frac{\partial u_i}{\partial X_1} dA \qquad (1)$$

where T_i is the traction force along the integration path Γ. W, n_1, ρ, u_i and A are the strain energy density, the X_1 component of the unit normal vector, the mass density, the displacement and the domain surrounded by Γ, respectively.

Figure 2 shows the calculated time variation of the applied electromagnetic load P_e, the reaction load at supported points P_s and the dynamic J-integral J_{dyn}, respectively. It is noted here that the J_{dyn}-integral takes the peak value at about 2msec. No serious higer mode oscillation is observed in the J_{dyn} vs. time curve. On the other hand, the supporting load P_s oscillates with the period of the natural oscillation of the part of the specimen outer from the supported point. However, as its value is always positive during the fracture event, it is expected that the specimen loaded by the electromagnetic force continues to contact with the supporting points, whose tendency differs from the experimental results for the fracture phenomenon impacted by mechanical loading [7].

Figure 3 shows nine kinds of time history of the electromagnetic load. Figure 4 shows the calculated relation between the J_{dyn}-integral and the deflection at the center of cracked specimen for the nine loading conditions given in Figure 3. It appears from the figure that the nine curves with various loading rates overlap with each other rather well. The similar relations between the J_{dyn}-integral and the COD_{mouth} and those between the COD_{mouth} and the deflection also show good coincidences with each other. The reason for the coincidence of these relations, irrespective of the different loading rates, may be explained by the fact that the deformation of the cracked beam under the dynamic electromagnetic force behaves always itself in a simple first natural eigen mode.

Thus, the dynamic electromagnetic force as a body force may help to reduce the higher-mode oscillation of the dynamically loaded specimen, and the unique relation between the J_{dyn} integral and the deflection is very useful for the purpose of fracture toughness evaluation.

Incidentally, it should be noted that the Joule heating concentrated around the crack tip due to the singularity of the electric current distribution affects more or less the fracture behavior of the cracked specimen carrying the electric current. Nevertheless, as shown in the previous study by the present authors [4,5], the influences of Joule heating on fracture phenomena subjected to electromagnetic force including the thermal stress and some change of material properties near the crack tip could be ignored practically to evaluate the J-integral value.

3. Experiments

3.1 Test System

The transient electric current conducting in the specimen is supplied by the LCR discharge circuit. The maximum capacity of the electric current is about 18kA at about 0.5msec with the voltage of 1000V. In order to apply a steady magnetic field to the specimen, a conventional electromagnet is employed except one test in which a newly developed superconducting magnet is preliminarily used.

The dynamic fracture toughness tests are performed at various temperatures from -196°C to 115°C with a single edge-cracked specimen made of nuclear pressure vessel steel A508 class 3. A saw notch is machined and then a fatigue pre-crack is given up to a length of a/W = 0.5 (a=crack length, W=width of test specimen). The thickness of specimen is decided to be 6mm considering the load capacity of the apparatus.

3.2 Fracture Toughness of A508 class 3 Steel

The diagram of K_{Id} testing procedure is illustrated in Figure 5. Below the transition temperature range where the fracture behavior is controlled by cleavage, the electric potential method using the transient electric current conducting in the specimen is utilized in order to detect the crack initiation time t_c, which is then used to determine the critical deflection value δ_c. Finally, the brittle fracture toughness of dynamic crack initiation $K_{Id}(J_c)$ is obtained from the critical J_c value, which is derived with the calculated J_{dyn}-integral vs. deflection curve.

The method proposed here to obtain the J_{Id} value for dynamic ductile fracture is based on the J-R curve technique, usually utilized in the static fracture test. As shown in Figure 6, each specimen is dynamically loaded up to a desired displacement δ_m (not to failure) by electrically controlled force and the corresponding J_{dyn}-integral, J_m value, is evaluated with the calculated J_{dyn}-integral vs. deflection curve. The fracture toughness J_{Id} is then determined as a cross point of the blunting line and the J-R curve.

The dynamic fracture toughness data vs. temperature obtained in the present study are plotted by solid marks and solid line in Figure 7. The ASME K_{IR} curve, the Japanese static data (hatched area) [8] as well as the other dynamic data (dashed line) [2] are also plotted in the figure for the purpose of comparison. The open symbols are our static data obtained from the same type of specimens as those used in the dynamic test. According to the finite element calculation for all the dynamic experimental results, the loading rate is in the range from 8×10^4 to 2×10^5 $MN/m^{3/2}sec$ in terms of $\dot{K}$. The figure shows that, below the transition temperature range, the dynamic toughness data seem to be smaller by about 30 to 50 percents than the static ones, and the transition temperature shifts by 40 to 50 degrees to the higher temperature range due to the loading rate effects. In the upper shelf temperature range, the dynamic toughness data are also reduced by 10 to 20 percents comparing with the static data. This tendency appears to be in accordance with the decreased shear rate observed in fracture surface for the dynamic cases. It is, however, required to test larger specimens to more accurately determine the fracture toughness data in the upper shelf range.

3.3 Strain Distribution near Crack Tip in Dynamic Fracture Process

The strain distribution near the crack tip in the dynamically fracturing specimen is obtained by using the high-speed movie technique and the computer picture processing [6] as shown in Figure 8. The pictures of the surface of the specimen marked with points using etching technique beforehand are taken with a high-speed movie camera (250μsec/film) during the dynamic fracture event. The digital data of the black and white picture of the specimen's marked surface are taken at each time stage with the Vidicon-camera (TV-camera) under control of the super mini-computer PRIME550 to which the data are sent and converted to 8-bit gray scale. In the first step of picture processing with a coarse picture of 256x256 pixels per frame, the number of marks and the rough mark locations are measured in order to set windows for the following processing. In the second step, the accurate mark locations are obtained in each window part of a fine picture which consists of 1024x1024 pixels per frame. Finally, using these locations decided, the least square approximation of the 2D distribution of the displacement, for the interpolation of which the finite element subdivision is used, is obtained, and then the strain distribution is determined from differentiation of the displacement field.

Figure 9 shows the high-speed film picture of marked specimen at the time of 2.5msec, and Figure 10 shows the distribution of the Green's strain λ_y near the crack tip obtained from the picture.

4. Conclusions

(1) To determine the dynamic fracture toughness of the nuclear pressure vessel steel A508 class 3 in brittle and ductile temperature regions, the dynamic electromagnetic force method is successfully employed.

(2) The dynamic strain distribution near the crack tip is obtained by using the high-speed movie technique and the computer picture processing.

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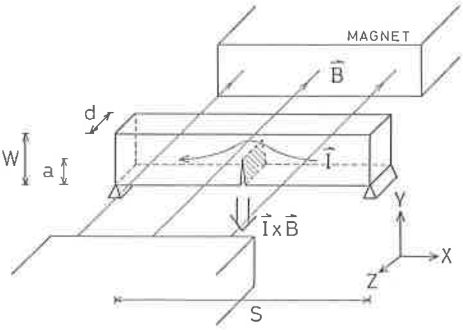

Figure 1 Edge-cracked beam under electromagnetic force

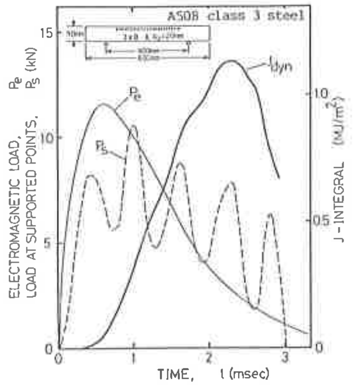

Figure 2 Electromagnetic load P_e, reaction load P_s and J_{dyn}-integral vs. time

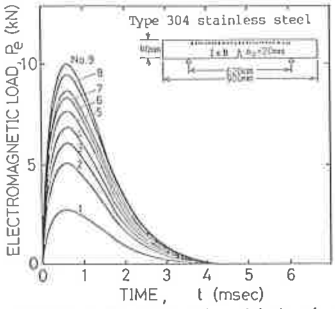

Figure 3 Various time histories of electromagnetic force

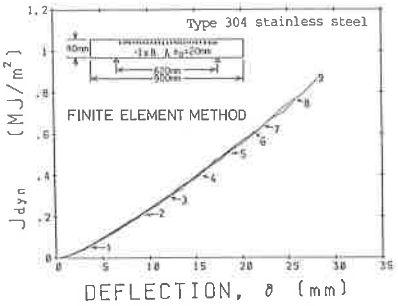

Figure 4 Calculated J_{dyn} vs. deflection curves for the loading conditions given in Figure 3

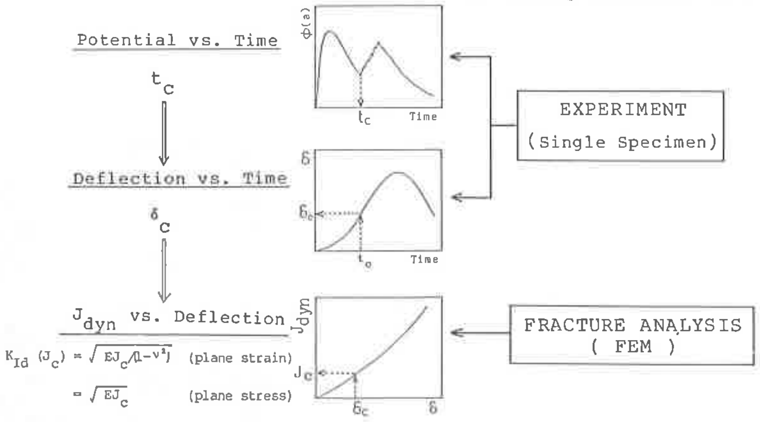

Figure 5 Diagram of K_{Id} determination for brittle material without stable crack growth -- electric potential method --

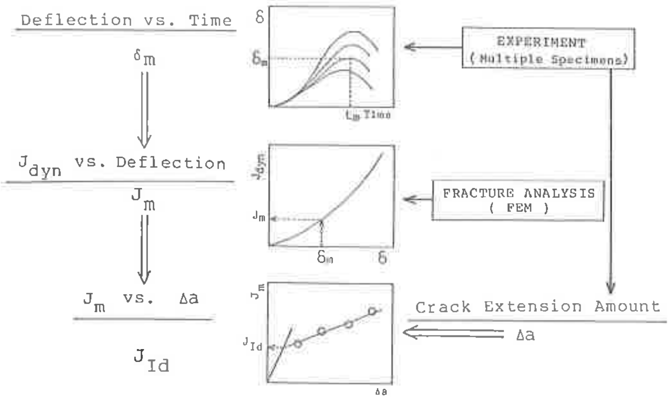

Figure 6 Diagram of J_{Id} determination for ductile material with stable crack growth -- J-R curve method --

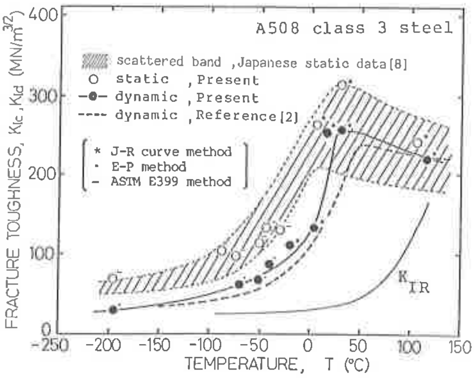

Figure 7 Fracture toughness of A508 class 3 steel vs. temperature

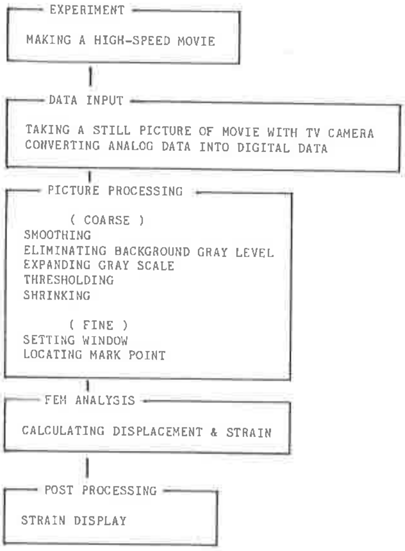

Figure 8 Flow chart of picture processing for dynamic strain measurement

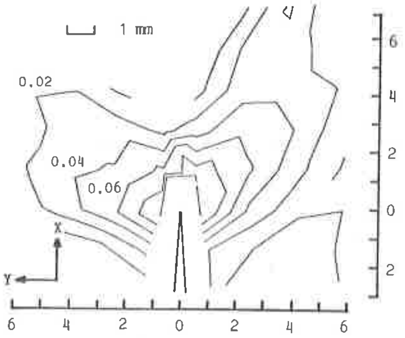

Figure 10 Green's strain distribution λ_y around the crack tip at 2.5msec

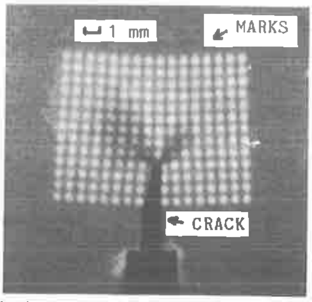

Figure 9 Marked surface of specimen at 2.5msec