ENERGY CONSIDERATIONS IN DYNAMIC CRACK PROPAGATION AND ARREST

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INTRODUCTION

Since the ship building industry has experienced a number of casualties due to brittle fracture, most naval architects have been forced to be interested in the brittle behavior of low and medium strength structural steels. While linear-elastic fracture mechanics was originated and applied to ultra high strength steels and other special alloys in space engineering in the United States, Japanese research groups were trying to use fracture mechanics to interpret the results of brittle fracture propagation arrest tests using wide plate specimens.

Within the limit of a relatively short arrested crack, a static approximation using either a linear fracture mechanics concept or an arrest toughness concept has yielded useful results for both the theoretical interpretation and the design application of currently used brittle fracture propagation arrest tests [1]. Later experimental investigations using very wide specimens (1,300 and 2,500 mm wide plates) have revealed that the above simple interpretation is inconsistent with results for long arrested cracks [2-4].

In order to seek a more reasonable theory of fast fracture and crack arrest and to study how neglect of dynamic aspects affects the interpretation of results of unstable, fast crack propagation arrest tests and the philosophy of crack design, the authors have started with a dynamic fracture mechanics analysis of crack propagation and arrest with the use of a finite-difference method. The results of the analysis were compared with previous data on structural steels and experiments using PMMA specimens, and are discussed in terms of dynamic fracture mechanics analysis.

BRITTLE CRACK PROPAGATION ARREST TEST USING VERY WIDE PLATE SPECIMENS

A simple fracture mechanics concept has been successfully applied to the analysis of the experimental results of several kinds of brittle crack arresters using medium size specimens (500 mm wide) [1]. This analysis is based on the arrest toughness concept and the assumption that the dynamic component of the stress intensity factor or strain energy release rate can be neglected, in so far as the crack length is relatively small, and a crack just before arrest or running at a speed near to the lower critical velocity of a brittle crack (200 ~ 400 m/sec [5]) is considered.

In the case of large welded steel constructions such as ships, the occurrence of a very large brittle crack is to be presumed. When a brittle crack extends to a very large-scale crack, however, it is questionable whether the above simple approach is valid or not. In relation to this

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 MS321

problem, extensive experimental research projects have been conducted in Japan, using very wide (max. 2,400 mm) plate specimens (gradient temperature type and hybrid type crack arrest tests) [2-4].

Figure 1 shows an example of test results for a gradient temperature type ESSO test plotted as log K_c vs. 1/T, where K_c is the nominal arrest toughness or static K value at the arrest point and T is absolute temperature. The solid circles denoted as DG are the data obtained from the standard double tension test (500 mm wide specimen, temperature gradient type crack arrest test), and they are considered to represent the material toughness against propagation which can be handled on the basis of a linear fracture mechanics criterion. Effect of load drop is taken into consideration in the sense of statics [6]. Figure 2 shows examples of crack speed measured in various types of arrest tests. It is to be noted that crack speed in the wide plate specimen is much higher than DG specimen for most of the propagation period.

The considerable discrepancy between K_c values obtained from wide specimens and those from standard specimens (DG specimens), as seen in Figure 1 suggests that estimation of K values (parameter characterizing crack driving force) on the basis of a simple static approximation is invalid, possibly due to disregard of dynamic features involved in extensive propagation of brittle crack such as is observed in the wide specimens.

DYNAMIC ANALYSIS USING FINITE DIFFERENCE METHOD

For the analysis of a dynamic crack in a plate, the following two-dimensional equations of motion in an elastic medium were used

$$\frac{\partial^2 u}{\partial t^2} = C_1^2 \frac{\partial^2 u}{\partial x^2} + (C_1^2 - C_2^2)\frac{\partial^2 v}{\partial x \partial y} + C_2^2 \frac{\partial^2 u}{\partial y^2} \qquad (1)$$

$$\frac{\partial^2 v}{\partial t^2} = C_2^2 \frac{\partial^2 v}{\partial x^2} + (C_1^2 - C_2^2)\frac{\partial^2 u}{\partial x \partial y} + C_1^2 \frac{\partial^2 v}{\partial y^2} \qquad (2)$$

where C_1 and C_2 are the dilatational and shear wave speed, respectively. u and v are the displacements in the x and y directions, respectively. Taking the x-axis as the crack line, dynamic analysis of a crack in a plate was made by solving equation (2) with relevant boundary and initial conditions using the finite-difference method.

The time increment Δt was chosen so as to meet the stability condition of the numerical solution [7]:

$$\frac{C_1 \Delta t}{h} = 0.5 \qquad (3)$$

where h is mesh spacing.

As a preliminary to examining the validity of the present method of analysis, several illustrative problems were solved. The width and length of the cracked plates analyzed were 50 ~ 100h. One of the illustrative problems solved was a crack extending in a plate (B=70h, H=70h) at constant speed from an initial crack length of 2a = 2 × 5.5h. The stress distribution

along the crack line is shown in Figure 3 compared with the analytical solution obtained by Broberg [8]. On other aspects such as deformation and energy flow, the numerical results compared well with the analytical solution except for the region close to the crack tip, which would be inevitable in using the finite difference method. Thus the present finite-difference method was shown to be useful for analysis of dynamic crack propagation, especially for higher crack speeds which necessitate that the dynamic effect be properly included.

NUMERICAL EXPERIMENT

Several numerical experiments were carried out on a plate (B=70h, H=70h) with an initial crack 2a = 2 × 5.5.h long, using a simple crack growth criterion which specifies the critical breaking stress σ_{Yc} at a fixed distance from the crack tip (point A in Figure 4). Examples of the crack speed obtained are shown in Figure 4. Figure 4(a) shows a result for a crack running through the field of uniform material resistance or constant critical stress for crack growth: σ_{Yc} (A)=3.0T. The crack is accelerated to a terminal speed and this agrees with many experimental observations so far reported. Figure 4(b) shows an example for a crack traversing a field of linearly increasing material resistance such as is the case with a temperature gradient type crack arrest test, the crack will be decelerated and finally be arrested in this case, and this compares qualitatively with experimental observations such as are shown in Figure 2. Figure 4(c) is a result for the case of decreasing applied stress with time, which simulates a crack subjected to a load drop effect and/or a crack running into a decreasing stress field such as occurs in a crack arrest test using a bending or wedge opening specimen with fixed grips.

DISCUSSION ON EXPERIMENTAL RESULTS

Experiment on PMMA

Using 10 mm thick PMMA, a series of crack arrest tests were conducted. The specimens used were single-edge-notched 300 mm wide and 280 mm long plates. The mean velocity of the crack was measured by crack detector gages mounted along the crack propagation line and the load drop was dynamically recorded. The measured crack speeds ranged from 120 to 540 m/sec, that is, relative speeds with respect to a dilatational wave (2.15×10^3 m/sec for the PMMA used) were 0.06 to 0.25. The experimental results were analyzed by the numerical method using the experimentally obtained crack speed and load as the time dependent boundary conditions. Figure 5 shows an example of the variation of the energy components with crack length i.e., work done by external load, W, kinetic energy, K, strain energy, U and dissipated energy, D.

The dissipated energy D, which is interpreted as material fracture energy, is obtained from law of conservation of energy given by

$$D = W - U - K \qquad (4)$$

where W, U and K are computed from experimentally obtained a vs. t and (load) vs. t relations. Dynamic fracture toughness K_d, which is defined by

$$K_d = E\left(\frac{dD}{da}\right)^{1/2} \qquad (5)$$

was computed taking several points on D vs. a and ȧ vs. a curves, and ȧ values are plotted against K_d, as shown in Figure 6, compared with the data obtained by Green et al [9]. With the limited experimental results it is hard to determine whether the material property associated with dynamic crack propagation is completely defined by an ȧ vs. K_d relation. The increasing trend in toughness with crack speed seems to support the experimental observation that the roughness of fractured surfaces increases with crack speed.

Experiment on ship steel

A similar analysis was made on the previously mentioned experimental result using a 2,400 mm wide steel plate specimen. An example of the energies calculated using experimental crack speed data is shown in Figure 7. This was a temperature gradient type ESSO crack arrest test with an arrested crack about 1,450 mm. The experimental observations showed that the fixed grip condition was approximately realized in this case. Figure 8 shows the variation of the K_d value calculated from the D curve with crack length compared with the static stress intensity factor K. The increasing trend in K_d with crack length is probably due to the same factors. It is to be noted that the K_d value is smaller than the nominal K value at the arrest point. The K_d value at the arrest point is nearly equal to the K_c value obtained from the small size arrest test (DG) on a static basis (Figure 1). However, the numerical evaluation of dD/da may involve considerable error, and further accumulation of data is needed in order to determine whether the present analysis is full enough to expalin such a discrepancy as is shown in Figure 4.

CONCLUSIONS

It is shown that dynamic analysis, using the finite-difference method, applied to the equation of motion in an elastic medium will provide a useful tool for investigation of the dynamic aspects of fast fracture and crack arrest. The preliminary study reported in this paper has shown that considerable refinement is needed in current theories of crack propagation and arrest. One of the main concerns is whether or not crack arrest is defined only by an energy condition.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge partial support of this research by the Ministry of Education of the Japanese Government, and the assistance in experiments and analysis given by Messrs. T. Teramoto and Y. Niimura of the University of Tokyo.

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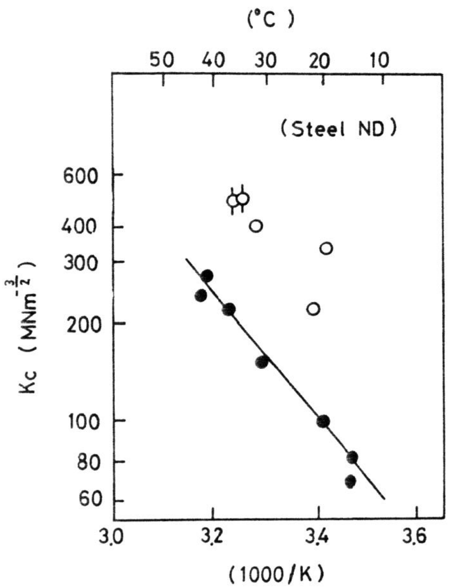

Figure 1 Relation between K_c value and temperature at crack arrest points (normalized D-class ship steel).

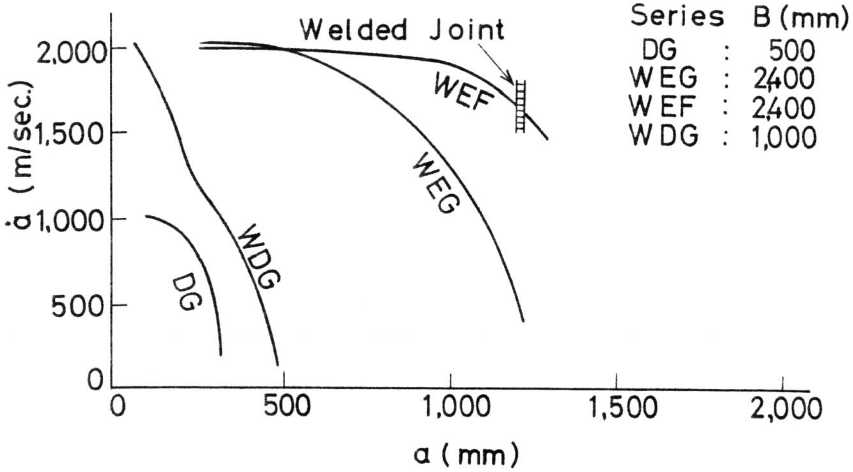

Figure 2 Comparison of crack speeds

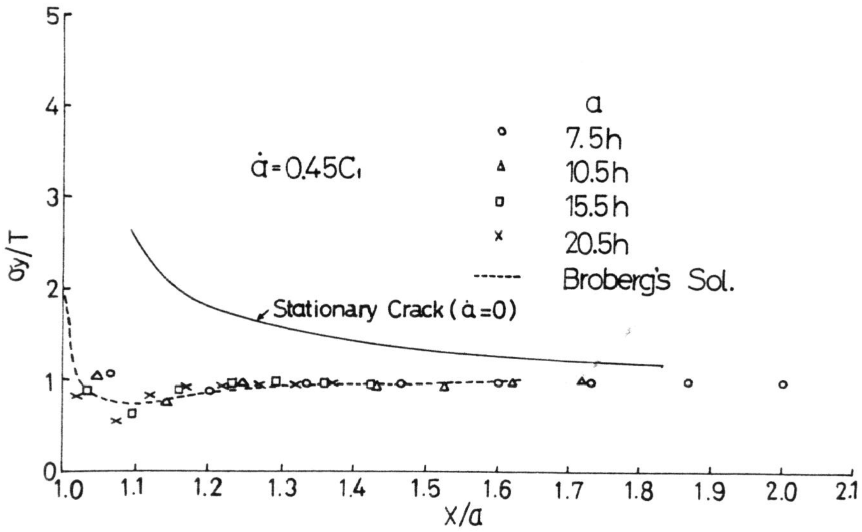

Figure 3 Stress distribution along the crack line of a crack extending at constant speed ($\dot{a} = 0.45C_1$)

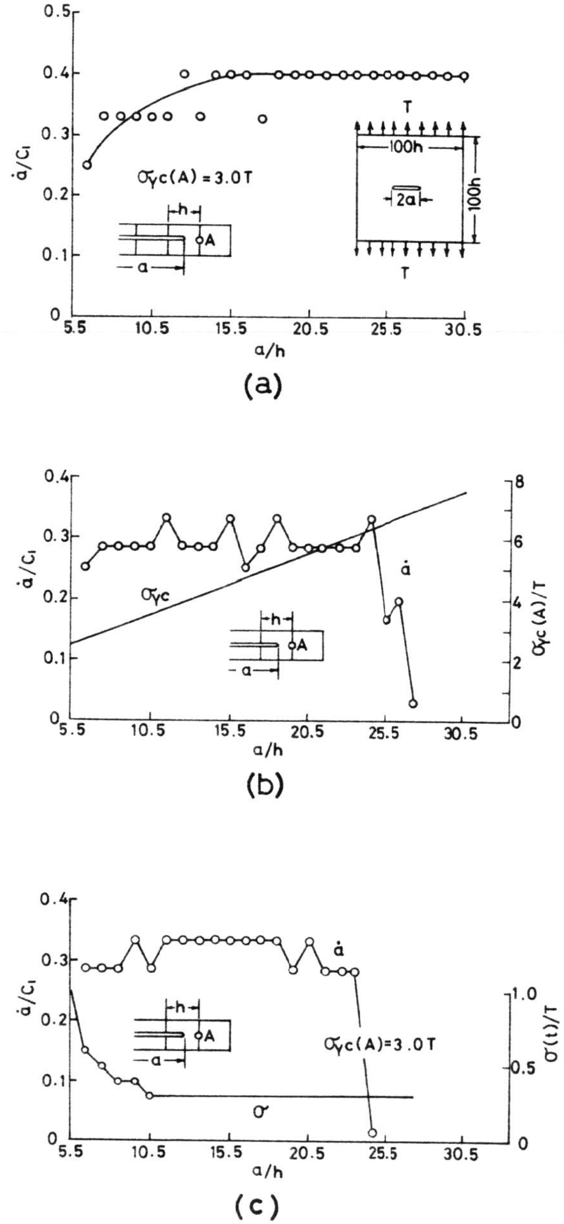

Figure 4 (a) Crack length variation of crack speed for a crack traversing a uniform stress and uniform material resistance field.
(b) Crack length variation of crack speed for a crack running into a linearly increasing material resistance field.
(c) Crack length variation of crack speed subjected to a load drop effect.

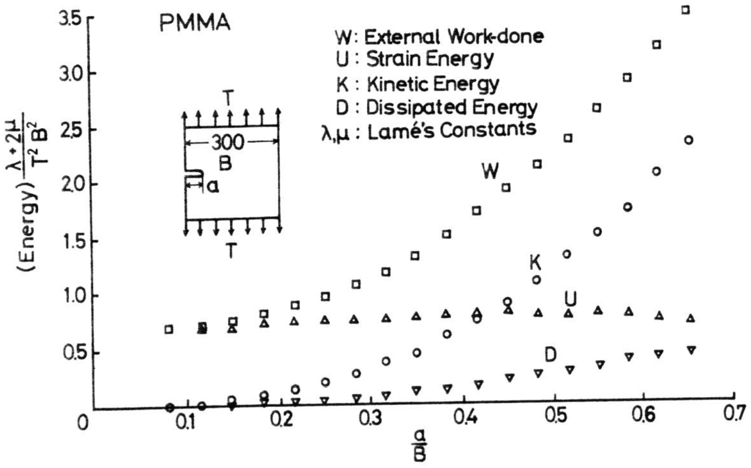

Figure 5 Energy changes with extension of a crack (PMMA)

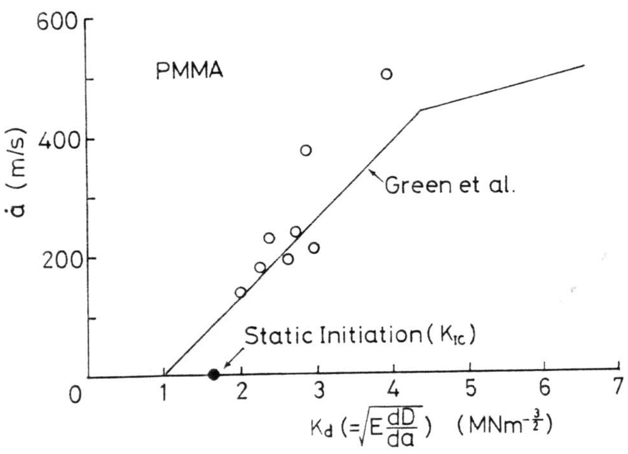

Figure 6 ȧ vs. K_d relation for PMMA

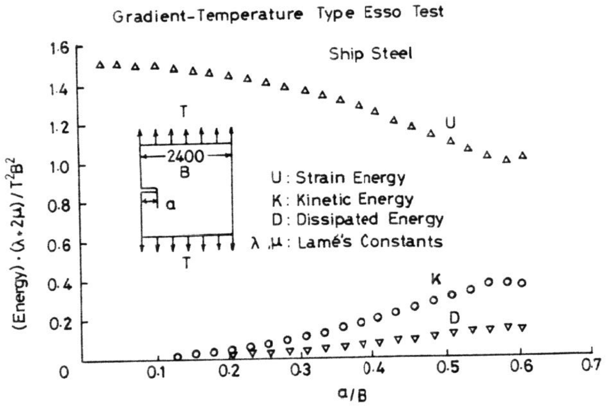

Figure 7 Energy changes with extension of a crack (ship steel)

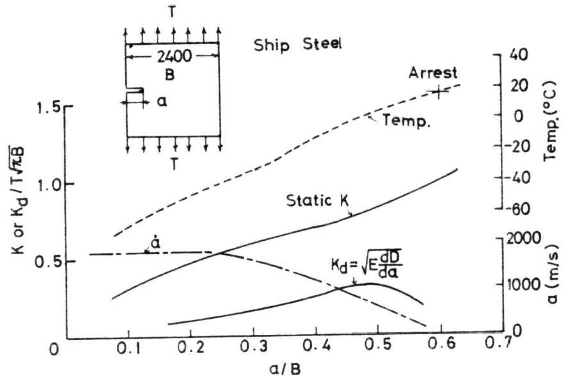

Figure 8 Arrest toughness compared with static K value