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Brittle crack propagation/arrest behavior in steel plate – Part II: Experiments and model validation

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ABSTRACT

The proposed model formulation for brittle crack propagation/arrest behaviors in a steel plate has been validated by comparing with experiments of temperature gradient and duplex crack arrest tests. The proposed model formulation successfully predicted the experimental results, such as (1) a deviation from the empirical knowledge in the relationship between arrest toughness and temperature evaluated by the temperature gradient tests, and (2) a transition region of the crack arrest behavior evaluated by the duplex tests. The results consequently showed a possible solution to "the long crack problem", which was not solved in the past studies.

1. Introduction

Brittle fracture has sometimes caused serious damages for large steel structures. The establishment of the crack arrest concept in addition to brittle fracture initiation control makes them provide "double integrity". This concept is essentially important for the integrity of some large structures whose accidental failure may involve significant social damages.

Nippon Kaiji Kyokai and International Association of Classification Societies (IACS) recently published a requirement on brittle crack arrest design [1,2]. The requirement was basically prescribed by using the arrest toughness K_{ca}, such as $K_{ca} \geqslant 190\,\mathrm{MPa}\sqrt{\mathrm{m}}$ (6000 $\mathrm{N/mm^{3/2}}$) to arrest any brittle crack propagation for steel plates with thickness of less than 80 mm. Although the requirement based on K_{ca} is certainly effective to prevent brittle crack propagation, it was established based on the experimental facts [3–8] but not on the fracture mechanics theory [9–11]. That is, the requirement of K_{ca}, which can arrest any length of cracks, cannot be explained by the linear fracture mechanics theory.

In the first part of this paper [12], we presented a new model formulation to quantitative simulate a brittle crack propagation and arrest in a steel plate. The proposed model formulation is based on the local fracture criterion, in the same manner as that of Aihara et al. [13–18]. The following three assumptions are additionally adopted for simplification of the fracture model to develop the new model formulation: (1) a shape of crack front is assumed as a straight line perpendicular to the crack propagation direction, (2) an uncracked side-ligament is regarded as a part of crack and affects the crack propagation driving force, and (3) an evaluation point for formulation of the crack propagation is only at the crack front in the

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Nomenclature

a	crack length
a_0	initial crack length for model simulation
k_0, K_0	material constants for the conventional estimation curve of dependence of K_{ca} on T expressed by Arrhenius equation
K	stress intensity factor
K_{ca}	arrest toughness
K_{sl}	crack closure effect of uncracked side-ligament as an expression of stress intensity factor
K_σ	stress intensity factor by remote applied stress
t	thickness of plate
T	temperature
V	crack velocity
W	width of plate
x	coordinate in width direction
σ_{app}	remote applied stress
σ_f	local fracture stress
σ_{Y0}	yield stress at room temperature

mid-thickness satisfying plane strain condition. These assumptions can make a significant merit for simplification of calculation, i.e., it takes only a few seconds for a simulation of a temperature gradient crack arrest test. The proposed model formulation simulates a brittle crack propagation and arrest behavior by simultaneously solving the following four equations on: (a) fracture condition, (b) strain hardening, (c) yield point and (d) dynamic stress intensity factor. When the equations are solved, the crack propagation continues and the values of variables composing the equations are obtained at each time step. On the other hand, the crack is predicted to be arrested when the equations do not give any solutions or when the uncracked side-ligaments cover all the thickness of the plate at the crack-tip. The brittle crack behavior can be therefore easily evaluated by the repeated calculations without any complicated calculations.

The aim of the present paper is to validate the new proposed model formulation in the first part of this paper by comparing with experiments and to solve "the long crack problem" [19] by simulating the brittle crack propagation and arrest behavior in steel plates.

2. Crack arrest tests

Brittle crack arrest toughness K_{ca} is a material parameter compared with the stress intensity factor K based on the linear fracture mechanics theory. That is, in the case of $K < K_{ca}$, the brittle crack can be arrested [1,19,20]. Although some kinds of crack arrest tests have been developed [19–28], the present study employs two types of brittle crack arrest tests: (a) temperature gradient crack arrest test and (b) duplex crack arrest test, whose configurations are shown in Fig. 1.

2.1. Temperature gradient crack arrest test

K_{ca} of a steel plate can be evaluated by a temperature gradient crack arrest test. The method of the test was published as a standard, WES 2815, by The Japan Welding Engineering Society (see Fig. 1(a)) [20]. The standard specifies precisely the testing conditions, including specimen configurations, impact energy limit, applied stress limit, etc. based on the related works [29–32].

It is known that K_{ca} increases with rising temperature, so that a crack is arrested at the location of $K = K_{ca}$ in the temperature gradient crack arrest test. Thus, K_{ca} can be evaluated as

$$K_{ca} = \sigma_{app}\sqrt{\pi a}\left\{\frac{2W}{\pi a}\tan\left(\frac{\pi a}{2W}\right)\right\}^{1/2} \tag{1}$$

where σ_{app} is an applied stress and a is an arrested crack length. Eq. (1) is called as "the tangent formula", considering the effect of specimen width W [19,33–36]. Different conditions of temperature and applied stress give a dependence of K_{ca} on temperature, which is empirically expressed by Arrhenius equation [19,33,34] as

$$K_{ca} = K_0 \cdot \exp(-k_0/T) \tag{2}$$

where T is temperature, and K_0 and k_0 are material constants. It is reported that the results of K_{ca} under excessively high applied stress condition are deviated from the dependence described in Eq. (2), so that such results are regarded as invalid cases and allowable range of the applied stress is provided in the standard [20].