EXPERIMENTAL STUDIES OF STABLE CRACK GROWTH IN A SINGLE TPB SPECIMEN

Lai Zuhan (赖祖涵) Ma Changxiang (马常祥)
Northeast Institute of Technology, China

ABSTRACT

An experimental method is presented which can be used to measure J and COD (δ) simultaneously and continuously by means of a single specimen. The criterion of stable crack growth is demonstrated. The relation between $\frac{dJ}{da}$ and $\frac{d\delta}{da}$, where a is the crack length, is established without any more theoretical assumptions. The experimental results agree well with the theoretical formulation presently available.

INTRODUCTION

Stable crack growth under plane strain condition in low and medium strength steels has been investigated by several researchers recently. These authors use $\frac{dJ}{da}$ and $\frac{d\delta}{da}$ to describe the growth behavior, where J and δ are respectively the J integral and the opening displacement at the original crack tip. In order to obtain the numerical values of $\frac{d\delta}{da}$ and $\frac{dJ}{da}$, one must either use finite element method or employ multispecimen method to determine J-Δa resistance curve. Both these have their own drawback. One needs a method to determine J and δ continuously at every instant when the specimen is in the "on load" condition. In this paper, we shall present an experimental method to study the crack growth behavior in a single TPB three-point bend specimen. The criterion for stable growth is demonstrated and the relation between $\frac{dJ}{da}$ and $\frac{d\delta}{da}$ is clearly shown without any more theoretical assumptions. This relation is basically in agreement with the result obtained by Shih[1], who used the HRR deformation field and finite element calculation. Moreover, our method also gives practically the same values as that obtained by a simple calculation shown below[2].

THE PRINCIPLE OF THE EXPERIMENTAL METHOD

1. The Method to Obtain $\frac{dJ}{da}$ from Single Specimen

We have shown in [3] that crack growth in a TPB specimen under increasing load can be expressed by the following equation:

$$\Delta a = \frac{(\Delta_p)_s - (\Delta_p)_c - \dfrac{m(\Delta_p)_c(P_s - P_c)}{P_c}}{\dfrac{2m(\Delta_p)_c}{W-a} + \dfrac{32P_c}{EBW}(1-\nu^2)f^2(\frac{a}{W})} \qquad (1)$$

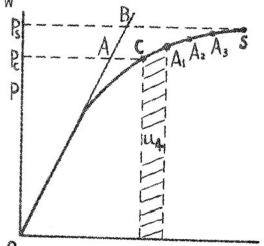

Fig. 1 Schematic diagram of P - Δ curve

Here Δa=the amount of crack growth after crack blunting had occured, usually $\Delta a \leq 0.50$ mm.

$(\Delta_p)_s$ = SB, plastic part of the load point displacement at the instant of unloading;

$(\Delta_p)_c$ = CA, plastic part of the load point displacement at the instant of crack initiation;

Δ = total displacement of the load point;

P = load, P_s and P_c are the loads at the unloading point and the crack initiation point respectively;

a = original crack length; W = width of the specimen;

B = thickness of the specimen; E = Young's modulus;

ν = Poisson's ratio.

Because Δa usually lies in the range 0.15-0.50mm, (W-a) and f^2 (a/W) can be evaluated at the original crack length without much error. f^2 (a/W) is found from calibrated tables. m is a parameter related to the work hardening capacity of the material and appears in the following equation given by Chen et al[4]:

$$(\Delta_p)_c = C\left\{\frac{P_c}{B(W-a)^2}\right\}^m \qquad (2)$$

Δa is measured on the fracture surface after unloading. Solve the simultaneous equations (1) and (2) with the aid of computer, we can find $(\Delta_p)_c$ and P_c. These are of prime importance for the location of the crack initiation point on a single P - Δ curve.

After the crack initiation point C has been obtained on a single P-Δ curve, we choose a neighboring point A_1, see Fig. 1. Substitute the

corresponding load P_{A_1} and $(\Delta_p)_{A_1}$ for P_s and $(\Delta_p)_s$ in (1), we could obtain the amount of crack growth up to A_1 and thus the current crack length a_1 at A_1 is known. The value of J at A_1 can be calculated by means of Garwood's formula[5]:

$$J_{A_1} = J_{1c}\frac{W-a_1}{W-a} + \frac{2U_4}{B(W-a)} \qquad (3)$$

where U_4 is the area under the curve between the points C and A_1.

By repeating such procedure, we can obtain J at each point in the interval from C to S. This gives J- Δa resistance curve from a single specimen. We are interested in the constant value of dJ/da for each curve. This is found by linear regression method.

2. The Method to Obtain dδ/da from Each Specimen

During continuous loading, δ at the original crack tip must be calculated by the following equation, as noted by Willoughby[6]:

$$\delta = \frac{r(W-a-\Delta a)+\Delta a}{rW+(1-r)(a+\Delta a)+Z}\left\{V - \frac{\beta\sigma_{0.2}W(1-\nu^2)}{E}\right\} \qquad (4)$$

where r=0.45,

V=knife-edge displacement,

Z=the thickness of the knife edge mounted at the crack mouth,

β=a constant which can be found from known table.

Because we are able to know Δa at every instant after crack growth by the above mentioned method, the curve of δ versus Δa can be determined from (4). dδ/da is also found by the linear regression method.

3. The Definition of CTOA (Crack Tip Opening Angle)

There are two definitions of CTOA. The first is:

$$\phi_n = 2\,t_g^{-1}\frac{\delta-\delta_i}{2(\Delta a)}, \quad \delta_i = \delta_{1c} \qquad (5)$$

δ always denotes the opening displacement at the original crack tip and Δa is the total amount of crack growth measured from the original tip. The second definition of CTOA emphasizes the opening displacement at the advancing tip, instead of the original tip. This is similar to that used by Rice-Sorensen[7]. We may define this angle alternatively as:

$$\phi_m = \frac{d\delta}{da} \qquad (6)$$

It is the derivative of $\delta(a)$ and can be found from (4).

EXPERIMENTAL RESULTS AND CONCLUSIONS

1. J-Δa and δ-Δa Curves Obtained by Single Specimen Method

Because of limited space, only a few curves are shown as illustrations, Fig. 2-3. It is clearly shown that, before the attainment of stable growth, there is transient behavior at the beginning of growth which can not be demonstrated by multispecimen method. Fig. 2 is a normalized curve of J/J_i against Δa, composing different heat treatments of 20CrMo steel.

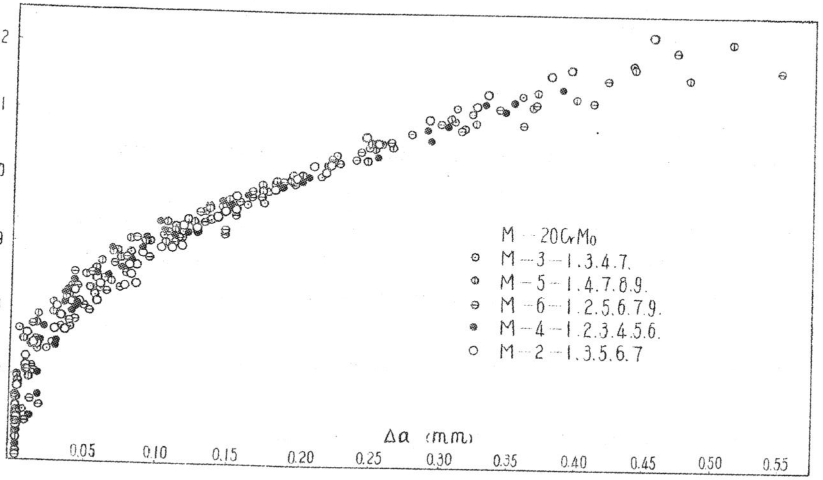

Fig. 2 J/J_i versus Δa curves of 20CrMo steel with different heat treatments

J_i is the J value when stable growth begins.

2. The Values of dJ/da, dδ/da and Tearing Modulus:

$$T_J = \frac{E}{\sigma_y^2}\left(\frac{dJ}{da}\right) \text{ and } T_\delta = \frac{E}{\sigma_y} M\left(\frac{d\delta}{da}\right)$$

Table 1 Values of dJ/da, dδ/da, T_J and T_δ

Materials	dJ/da kgf/mm²	dδ/da (rad)	M	T_J	T_δ	$\omega=\frac{W-a}{J_0}\frac{dJ}{da}$
Ti-D-4	36.07	0.339	1.27	118.99	113.71	23.46
T-D-9	38.17	0.400	1.53	193.98	199.46	30.46
L-D-2	38.67	0.280	1.92	165.35	161.10	15.73
L-Z-5	40.76	0.352	1.79	174.27	188.59	15.14
M-2-6	8.89	0.0952	1.02	20.63	21.47	13.76

Here $\sigma_y = \frac{1}{2}(\sigma_{0.2}+\sigma_{uts})$, J_0 in the expression of ω denotes the value when stable crack growth begins. Obviously $J_0 > J_{1c}$. M is the slope of the line representing J/σ_y versus δ (see Fig. 4) and can also be determined by taking the average of $J/\sigma_y\delta$ at each instant during crack growth. Both give practically the same value for each specimen. According to the literature, $\omega >> 1$ will indicate the fulfilment of the condition of J controlled growth.

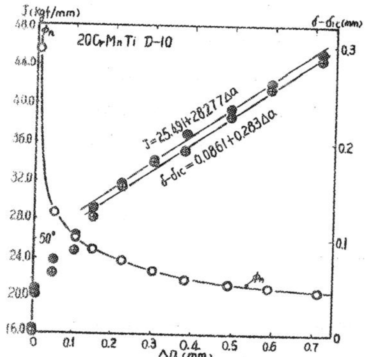

Fig. 3 The variation of J, δ and ϕ_n with Δa in 20rMTi

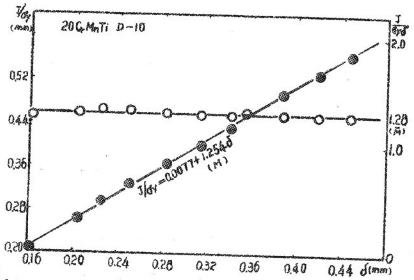

Fig. 4 Two alternative methods used to determine M for each specimen

3. Variations of ϕ_n and ϕ_m

From Fig. 3, it is clearly seen that ϕ_n decreases continuously when

Δa increases. But ϕ_m shows different trend, it becomes constant during stable crack growth. This is shown by the constant slope of the straight portion of δ versus Δa diagram. The criterion of stable crack growth can thus be expressed as the constancy of $d\delta/da$ or equivalently, the constancy of dJ/da. In formulating the criterion of stable crack growth, it is preferable to use ϕ_m instead of ϕ_n.

4. The Relation between dJ/da and dδ/da

Our experimental results indicate that

$$\frac{d\delta}{da} = \frac{1}{M_s \sigma_{0.2}} \left(\frac{dJ}{da}\right) \quad (7)$$

during crack growth. Shih[1] through his analysis of the deformation field, concluded that

$$\frac{d\delta}{da} = \frac{1}{M_s \sigma_{0.2}} \cdot \frac{m}{1+m} \cdot \frac{dJ}{da} \quad (8)$$

and M_s lies between 1.54—2.04 obtained by finite element calculation. Here we use 1/m in place of the work hardening exponent n, because we believe the parameter 1/m used in our paper may be more suitable to describe the work hardening in the crack tip region than the exponent n. The difference between (7) and (8) is a factor m/(1+m), which is usually 0.87-0.96.

On the other hand, by extending the formulation of a stationary crack to a slowly moving crack with only limited amount of growth, we use the following relation [2]:

$$M_s \approx \frac{m}{1+m} \cdot \frac{P}{B(W-a)^2 r} \cdot \frac{S}{2\sigma_{0.2}} \quad (9)$$

where S is the span of the specimen, r=0.45. The experimental determinations of M_s are compared in Table 2 with that obtained from (9), the values of m and P are taken at the beginning of stable crack growth.

These values are the averages from 8-11 specimens. The above results are quite satisfactory. It indicates that our experimental results agree quite well with those of Shin and eqn. (9) if the latter is used in the case of slowly moving crack.

Table 2 The comparison of the experimental M_s with that obtained from eqn. (9)

Materials	M_s experiemental results	M_s obtained from (9)
20CrMnTi	1.46	1.42
#45	1.92	1.89
40Cr	1.78	1.82
20CrMo	1.23	1.16

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