Consideration on Evaluation of Fracture Toughness and Testing Methods

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Abstract

The evaluation of fracture toughness is very important when we predict ultimate strength of material. The standard testing method for fracture toughness evaluation is already proposed. However, making an experiment using the standard test method is a little complicated including production of a loading apparatus.

In this study, fracture toughness K_{IC} is estimated by some easy testing methods using the model that can evaluate a stress intensity factor K_I. The acryl resin specimen that shows a linear behavior is used for the experiment, and K_{IC} is evaluated using the maximum load. The error over each testing method is investigated, and the strong and weak point for each procedure is discussed.

Key Words: fracture toughness, K_{IC}, testing method, acryl resin, testing accuracy

1. Introduction

Fracture mechanics is an engineering discipline, where the aim is to give a quantitative description of the transformation of an intact structural component into a broken one by crack growth. In its most basic form, it relates the maximum permissible stress to the size and location of a crack. It can also predict the rate at which cracks grow to a critical size, by environmental influences or by varying loads(fatigue). Further it can determine the conditions of rapid propagation and arrest of moving cracks.

Fracture mechanics is primarily used to prevent and predict catastrophic failure of structure of man-made materials such as metals, plastics, and ceramics. Historically fracture mechanics is a development of the strength approach of materials, in which the stress in a structure is compared with some material strength value in order to decide whether failure will occur or not. The basic material parameter in fracture mechanics is called the fracture toughness.

As for the evaluation method of fracture toughness, the theory is based on the linear elastic theory. The evaluation of fracture toughness is quite complicated in order that almost all material may show a nonlinear behavior. Moreover, it is difficult to obtain the fracture toughness that mean inherent characteristic for the material, or the fracture toughness as the judgment standard value for a crack extension. So, the fracture toughness currently obtained is considered to be the rough estimate value of the strength for a crack extension. If you want to obtain the standard of strength for a crack extension, it is more rational to use a simple method.

Now, there are two kinds of the standard testing methods[1] for fracture toughness evaluation. One is a compact tension test, and another is three points bend test. However, many simple testing methods, such as a single edge cracked plate tension test and a center cracked plate tension test, can be considered as a method of evaluating fracture toughness.

In this study, an acryl resin that shows a linear behavior is used for material, the specimens that a size differs are prepared, and six kinds of fracture toughness testing methods are tried. The dispersions over each the experimental results are investigated and the validity of each testing method is discussed.

2. Testing Methods for Fracture Toughness Evaluation of Mode I

The fracture toughness is estimated respectively independently by the opening mode (Mode I), the sliding mode(Mode II), the tearing mode (Mode III). However, the generality is considered and the fracture toughness evaluation is restricted to Mode I in this study. Although it is possible to perform many Mode I testing methods, the treated testing methods are the following six kinds of tests.

(1)Double edge cracked plate tension test[2),3)] (DECT)

(2) Single edge cracked plate tension test[4),5)] (SECT)

(3) Single edge cracked three point bending

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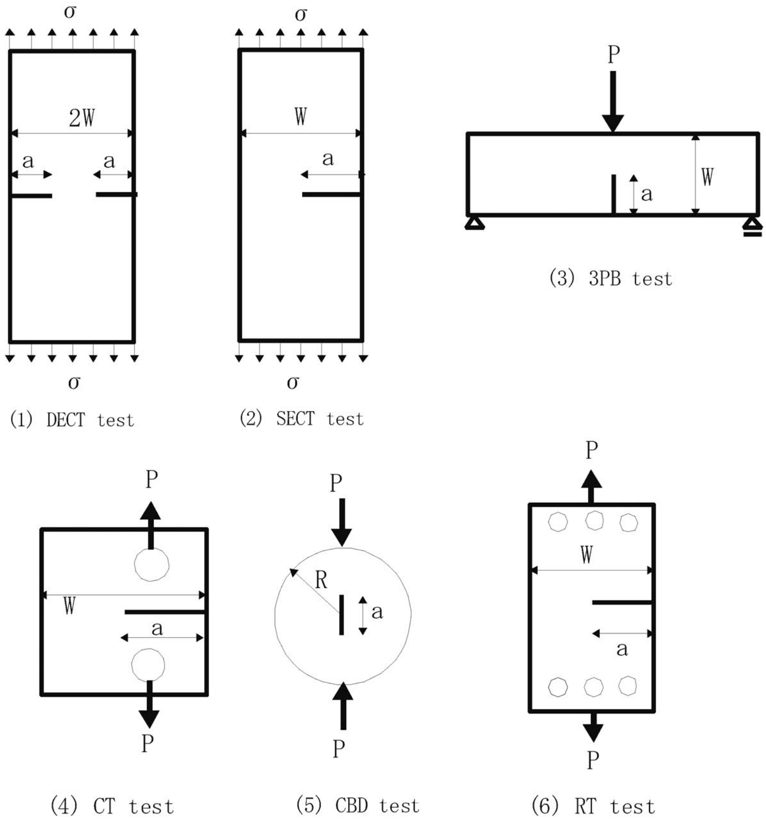

Fig. 1 The general views of K_{IC} tests in this study

test[4),6),7)] (3PB)

(4) Compact tension test[6),8)] (CT)

(5) Center slant cracked circular plate subjected to compression load[9)] (CBD)

(6) Single edge cracked test for mixed mode loading dvice[10)] (RT)

In these tests, the experiment of (5) and (6) is one of the mixed mode testing methods and is performed as part of a mixed mode test. Although the tests of (2) and (6) are same in the type to pull a single edge cracked plate specimen, the joint of the loading apparatus and the specimen is the type to grasp for the former and the type of pin joint for the latter. So, although the evaluation of the stress intensity factor of (2) is based on stress, (6) is based on load. The general views of these tests are shown in **Fig. 1**.

3. Experiment

The acrylic resin (poly-methyl methacrylate : PMMA) which shows the deformation and failure behavior near a linear elastic body was used as a material of experiment specimens. The material property of acryl resin is shown in **Table 1**.

Table 1 Material property of acryl resin.

Tensile strength	74.5 MPa
Bending strength	117.7 MPa
Compressive strength	123.6 MPA
Shearing strength	61.8 MPa
Young's modulus	2.94 GPa

The outline of a specimen size is shown in **Table 2**. The specimen size of DECT test is one kind of size, which has 5 specimens with notch length a= 10mm, specimen width W= 20mm, specimen thickness t= 2mm, specimen length ℓ = 160mm. The specimen size of SECT test is two kind of size, which have 5 specimen with notch length a= 20mm, specimen width W= 40mm, specimen thickness t= 2mm, specimen length ℓ= 160, and 6 specimens with notch length a= 100mm, specimen width W= 200mm, specimen thickness t= 2mm, specimen

Table 2 The kind of specimens

Group name	Specimen number (n)	Notch length (a ; mm)	Specimen width(W;mm)	Specimen thickness(t;mm)	Specimen length(ℓ;mm)
DECT	5	10	20	2	160
SECT1	5	20	40	2	160
SECT2	6	100	200	2	550
3PB1	5	15	30	30	150
3PB2	6	14,15,16	30	30	140
CT1	5	60	120	2	144
CT2	3	20	40	2	48
CT3	3	60	120	10	144
CBD	3	20	100	10	100
RT	3	30	60	2	120

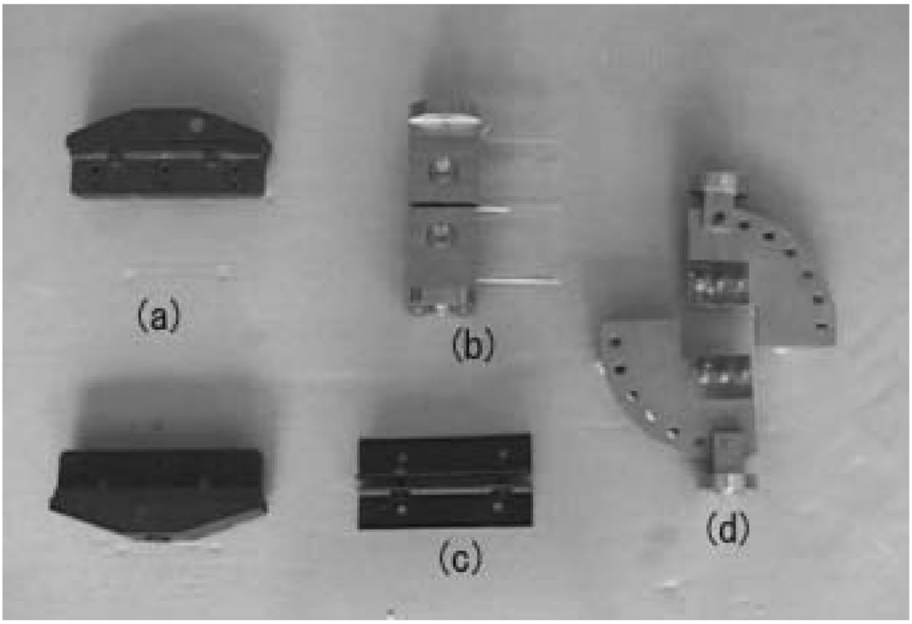

Fig. 2 Loading equipment, (a) is for DECT test and SECT test, (b) is for CT test (with big size specimen), (c) is for CBD test(top view), and (d) is for RT test.

length ℓ= 550mm. The 3PB test is performed a series of test twice. First test has 5 specimens with notch length a= 15mm, specimen width W= 30mm, specimen thickness t= 30mm, specimen length ℓ= 150mm. Another test is prepared 6 specimens with a different notch length, 14mm, 15mm and 16mm. The span length is 120mm. CT test has three kind of size. The specimen number is three respectively to each test kind. The details are shown in **Table 2**(CT1, CT2, CT3). The specimen size of the CBD test and the RT test is one kind. The CBD test has 3 specimens with notch length a= 20mm, specimen radius R= 100mm, and specimen thickness t= 10mm. The RT test has 3 specimens with notch length a= 30mm, specimen width W= 100mm, specimen thickness t= 2mm, and specimen length ℓ=120.

Although all specimens are made by machining progress, the notch tip is processed by hand with the cutter knife.

In these experiments, two electro-hydraulic fatigue testing machines, whose capacities for static loading are 15kN and 450kN, is used. Each

Fig. 3 Set up of three point bend specimen in testing machine

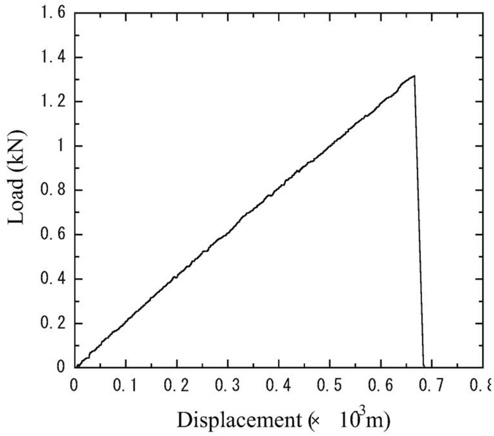

Fig. 4 Typical relationship between load and load point displacement in SECT1 group.

of loading equipment is shown in **Fig. 2**. In CBD test, the specimen fixed in the equipment (c) (**Fig.2**) is loaded using loading plate for compression test. In all tests, the average stress intensity factor rate during the test shall be not less than about $0.002MPa\sqrt{m}$ or such that failure occurs within about 10 min of initial load application. The set up of three point bend specimen in testing machine is shown in **Fig. 3**.

4. Conclusion and Discussion

The typical relationship between load and load point displacement in the test for SECT2 group is shown **Fig.4**. As shown in this figure, the relation of load and load point displacement shows a liner behavior in all examinations.

Fracture toughness K_{IC} is acquired by substituting the maximum load for an evaluation formula respectively. The used evaluation formula is shown below.

(1) DECT test[2)]

$$K_I = \sigma\sqrt{\pi a}F_I(a/W), \quad a/W = \xi$$

$$F_I(a/w) = \left(1 + 0.122\cos^4\frac{\pi\xi}{2}\right)\sqrt{\frac{2}{\pi\xi}\tan\frac{\pi\xi}{2}}$$

(2) SECT test[4)]

$$K_I = \sigma\sqrt{\pi a}F_I(a/W), \quad a/W = \xi$$

$$F_I(a/w) = 1.12 - 0.231\xi + 10.55\xi^2 - 21.72\xi^3 + 30.39\xi^4$$

(3) 3PB test[6)]

$$K_I = \frac{3SP}{2W^2B}\sqrt{\pi a}F_I(a/W), \quad a/W = \xi$$

$$F_I(a/w) = \frac{1.99 - \xi(1-\xi)(2.15 - 3.93\xi + 2.7\xi^2)}{\sqrt{\pi}(1+2\xi)(1-\xi)^{3/2}}$$

(4) CT test[6)]

$$K_I = P/(B\sqrt{W})F_I(a/W), \quad a/W = \xi$$

$$F_I(a/w) = \frac{2+\xi}{(1-\xi)^{3/2}}(0.886 + 4.64\xi - 13.32\xi^2 + 14.72\xi^3 - 5.6\xi^4)$$

(5) CBD test[9)]

$$K_I = \frac{1}{\sqrt{\pi a}}\int_{-a}^{a}\sigma_\theta(\theta,\rho)\left(\frac{a+\rho}{a-\rho}\right)^{1/2}d\rho = F_I(\beta)\frac{P}{Rt}\sqrt{\frac{a}{\pi}}$$

where θ and ρ are the variables in polar coordinates, and $F_I = 1.06$ for Mode I with $\beta = 0$.

(6) RT test[10)]

$$K_{\rm I} = \frac{P\sqrt{\pi a}}{WB}\cdot\frac{\cos\alpha}{1-\xi}\sqrt{\frac{0.26 + 2.56\left(\frac{\xi}{1-\xi}\right)}{1 + 0.55\left(\frac{\xi}{1-\xi}\right) - 0.88\left(\frac{\xi}{1-\xi}\right)^2}}$$

where $\alpha = 0$ for Mode I and $\xi = a/W$.

All fracture toughness K_{IC} values obtained in this study are shown in **Table 3**. The average value of fracture toughness, standard deviation, and the value that divide standard deviation by average value as the error are also respectively shown in the table for the experiment group.

Table 3 Experiment results contained experiment error

Group Name	Notch Length (mm)	Specimen Width (mm)	Specimen Thickness (mm)	Fracture Load (kN)	Fracture Toughness $K_{IC}(MPa\sqrt{m})$	Average Fracture Toughness	Error (%)
DECT	10.2	40.0	2.0	0.469	1.229	1.196 ±0.201 $MPa\sqrt{m}$	16.8
	10.3	39.9	2.0	0.376	0.992		
	10.4	40.0	2.0	0.375	0.990		
	10.3	40.0	2.0	0.584	1.536		
	10.5	39.9	2.0	0.460	1.231		
SECT1	20.9	40.0	2.0	0.228	1.255	1.332 ±0.094	7.1
	21.0	39.9	2.0	0.267	1.496		
	21.5	40.0	2.0	0.214	1.258		
	20.4	40.0	2.0	0.244	1.272		
	21.2	40.2	2.0	0.246	1.380		
SECT2	100.0	200.0	2.0	0.720	1.609	1.443 ±0.162	11.2
	100.0	199.9	2.0	0.734	1.662		
	100.0	201.0	2.0	0.671	1.480		
	101.0	200.0	2.0	0.615	1.404		
	101.0	201.0	2.0	0.580	1.306		
	101.0	201.0	2.0	0.531	1.196		
3PB1	14.9	30.1	30.1	0.892	1.785	1.618 ±0.099	6.1
	14.9	30.1	30.0	0.781	1.568		
	14.8	30.1	30.1	0.749	1.483		
	14.9	30.0	30.0	0.794	1.610		
	14.9	30.1	30.1	0.821	1.643		
3PB2	14.0	30.1	30.8	0.926	1.652	1.549 ±0.095	6.1
	14.0	30.1	30.7	0.876	1.567		
	15.0	30.0	30.7	0.833	1.668		
	15.0	30.1	30.8	0.780	1.541		
	16.0	30.0	30.9	0.631	1.400		
	16.0	30.1	31.1	0.672	1.465		
CT1	60.9	119.8	2.0	0.082	1.174	1.274 ±0.060	4.7
	60.1	119.9	2.0	0.090	1.260		
	60.9	119.8	2.0	0.089	1.274		
	60.9	120.0	2.0	0.095	1.356		
	60.7	120.0	2.0	0.092	1.304		
CT2	20.5	40.0	2.0	0.060	1.506	1.539 ±0.064	4.2
	29.9	39.4	2.0	0.060	1.483		
	21.0	40.5	2.0	0.064	1.628		
CT3	60.0	120.0	10.0	0.496	1.383	1.298 ±0.085	6.5
	60.0	120.0	10.0	0.435	1.213		
	60.0	120.0	10.0	0.445	1.241		
CBD	20.0	100.0	10.0	10.388	1.757	1.707 ±0.040	2.3
	20.0	100.0	10.0	9,800	1.658		
	20.0	100.0	10.0	10.094	1.707		
RT	30.0	60.0	2.0	0.267	1.891	1.851 ±0.108	5.8
	30.0	60.0	2.0	0.276	1.959		
	30.0	60.0	2.0	0.241	1.704		

The value of fracture toughness is distributed widely from 1.19 to 1.85. The experiment group of DECT shows the maximum error, 16.8%, and the smallest fracture toughness. Speaking of experiment accuracy, the experiment groups of SECT show the comparatively large experiment error. By these things, as for the testing method with the type that grasps and pulls specimen, it is guessed that the eccentricity of load tends to happen. The experiment groups of CBD and RT show comparatively large fracture toughness. Here, it may be necessary to take a contact surface into consideration for a CDB examination, and, as for RT, the component of Mode III may be contained in loading. The comparatively large fracture toughness also for 3PB tests is shown. This is considered because the thickness is large and plane-strain fracture did not take place. In CT tests, the small specimens give the comparatively large fracture toughness. Judging from experiment accuracy, 3PB test and CT test, which are adopted as the standard testing method, are effective. However, if it says from viewpoints, such as preparation of loading equipment, 3PB test and CBD test are useful.

It is estimated by the above thing that inherent fracture toughness is about 1.3 $MPa\sqrt{m}$. It is important for every testing method not to make the eccentricity of load cause. If it says from synthetic view, CT test and 3PB test using specimen with comparatively small thickness will be able to judge as the excellent testing method.

In this research, the fracture toughness of an acrylic resin by using the various fracture toughness testing methods has been evaluated. As a result, it is shown that 3PB test and CT test with comparatively thin thickness, which are the standard testing methods, are easy to treat for the exception of load eccentricity.

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