FATIGUE CRACK GROWTH AND ITS TIP OPENING DISPLACEMENT IN CARTRIDGE BRASS

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ABSTRACT

In the paper, the function describing the crack tip opening displacement (CTOD) is newly introduced. The form of the CTOD-function was decided analytically, based on linear fracture mechanics applying G.R.Irwin's model with von Mises yield criterion, on the relationship between required thickness for fracture toughness test and plasticity shaped around crack tip keeping plain strain state, and on the considering transition of crack growth rate with stress intensity factor range effected by cycle rate and cycle ratio, with variables, such as stress intensity factor range, Young's modulus, yield stress, Poisson ratio, and other coefficients. The coefficients were empirically determined by the data attained from fatigue test. Then CTOD was numerically computed and collated with detected CTOD and with striation space which were examined in SEM photo. As a result, the numerically calculated CTOD had a good accordance with experimental data. But the few differences between them are thought to be caused by zigzag progress of fatigue crack.

KEYWORDS

Fatigue crack propagation; crack tip opening displacement; cartridge brass; plastic zone size; thickness of specimen, transition point of stress intensity factor range

INTRODUCTION

The crack tip opening displacement (CTOD) is the key element to grasp the crack growth so there are a lot of researches on its phenomenon, mechanism and computation, such as [1] to [4] and others. In the study, the integrated formula was derived theoretically and empirically for finding out the way to predict the fatigue CTOD, particularly aiming at the transition of crack growth rate versus stress intensity factor range [5], [6] and the ratio of plate thickness of specimen to plastic zone size at the crack tip, which is required by ASTM E399 of fracture toughness test to preserve plain strain state. And for verifying it the obtained relationship, the fatigue test had been carried out and the cracked specimen was examined by SEM to clarify the CTOD and striation space quantitatively, and some differences between computed CTOD and detected data and striation-space are explained qualitatively by the examined cracked path.

THEORETICAL DETAILS

Generally, the stress intensity factor, K_1, is defined by equation (1) in linear fracture mechanics, where σ is mean stress and **a** is a length of crack.

$$K_1 = \sigma\sqrt{\pi a} \qquad (1)$$

On the presumption of small scale of yielding, the crack tip opening displacement, Φ, in the Irwin's model could be expressed approximately as a function (2), where E' is $E/(1-v^2)$, E is Young's modulus and v is Poisson ratio, and ω is plastic zone size at crack tip as shown in Fig.1.

$$\varphi_S = \frac{4K_1}{E'}\sqrt{\omega_s / \pi} \qquad (2)$$

In plain strain state, from von Mises yield criterion, the plastic zone size at crack tip can be expressed statically as function (3) as below, where σ_{ys} is proof stress.

$$\omega_S = \frac{1}{2\pi}\left(\frac{K_I}{\sigma_{ys}}\right)^2 (1-2v)^2 \qquad (3)$$

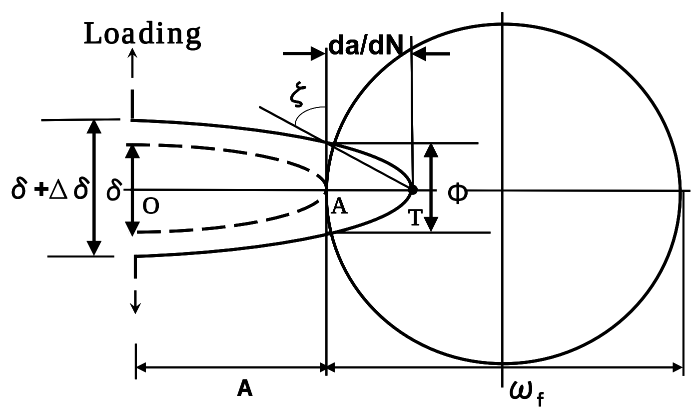


Fig.1 Schematic illustration of opening fatigue crack

From equations (2) and (3), the next equation (4) could be obtained.

$$\varphi_S = \frac{4\sqrt{2}\cdot\sigma_{ys}\cdot\omega_S}{E'(1-2v)} \qquad (4)$$

It is understandable that the relationship between CTOD and crack tip plasticity could exist also in fatigue test as in equation (5).

$$\varphi_f = \frac{4\sqrt{2}\cdot\sigma_{ys}\cdot\omega_f}{E'(1-2v)} \qquad (5)$$

In fracture toughness test, for keeping plain strain state, the least thickness, t_c, of specimen is given by next condition of (6) [7].

$$t_c = 2.5\left(\frac{K_{1c}}{\sigma_{ys}}\right)^2 \qquad (6)$$

It could be realized that the plain strain state could be existed critically at the ratio as shown in the next (7) that is related to the least thickness of plate specimen and the critical crack tip plasticity.

$$\zeta^{-1} = \frac{t_c}{\omega_{sc}} \qquad (7)$$

Namely, the next relationship (8) shall be established at critical point just to preserve plain strain state in specimen.

$$t \cdot \zeta = \omega_f = \frac{1}{\Omega} \cdot \left(\frac{\Delta K}{\sigma_{ys}} \right)^2 \qquad (8)$$

In the curve of da/dN vs. ΔK, the relations of Paris's rule comes off gradually at transition of crack growth rate, while the state of plain strain becomes incomplete and progressively changing to plain stress. Base on the transition phenomenon, the function parameter, Ω(f,t,R), could be determined empirically by repeated cycle rate of f and cycle ratio of R as shown in the form of (9).

$$\Omega = n \cdot (1 - R)^m \cdot f^B \qquad (9)$$

Then the fatigue plastic zone, ω_f, can be obtained in the form of the next (10).

$$. \ \omega_f = \frac{1}{n \cdot (1 - R)^m \cdot f^B} \left(\frac{\Delta K_1}{\sigma_{ys}} \right)^2 \qquad (10)$$

Then the formula (11) of CTOD could be decided by replacing function (10) into (5).

$$\varphi_f = \frac{4\sqrt{2} \cdot \Delta K_1^{\ 2}}{n \cdot (1 - R)^m \cdot f^B E' (1\text{-}2\nu) \cdot \sigma_{ys}} \qquad (11)$$

MATERIALS AND EXPERIMENTAL PROCEDURE

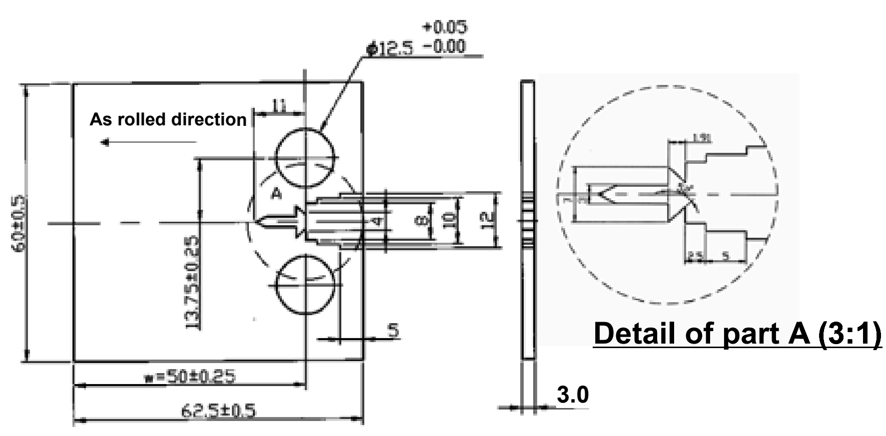


Fig.2 Illustration of CT specimen

CT specimens were fabricated In conformity with a rule of ASTM647 [8] from cartridge brass, JIS C2600P-1/2H of JIS H 3100. Its chemical composition and mechanical properties are as shown in Table 1 and Table 2. The thickness of specimen is 3mm and the width of specimen is 50mm. Fatigue tests were carried out in fatigue test machine, Shimadzu servopulser EHF-EB-10, with cyclic sinusoidal load with amplitude at constant load ratio and cyclic frequency in the air. The crack opening displacement along the tensile axis and the crack length corresponding to the number of cycles were detected and recorded. In several tests, the progressive fatigue crack was filmed by digital microscope with video camera. The cracked CTOD was examined by SEM, supposing its CTOD may be reproduced at the same crack length by giving the same ΔCOD as in carried out fatigue test, aiming to confirm theoretically predicted CTOD. The crack progress was photographed by an animation consecutively.

Cu	Fe	Pb	Zn
69.7	0.003	0.003	Residual

Table 1: Chemical composition in weight percent

Tensile Strength	0.2% proof stress	Young's modulus	Elongation rate	Poisson ratio
MPa	MPa	GPa	%	
360	174	96	28	1/3

Table 2: Mechanical properties of specimen

RESULTS AND DISCUSSION

Transition phenomenon

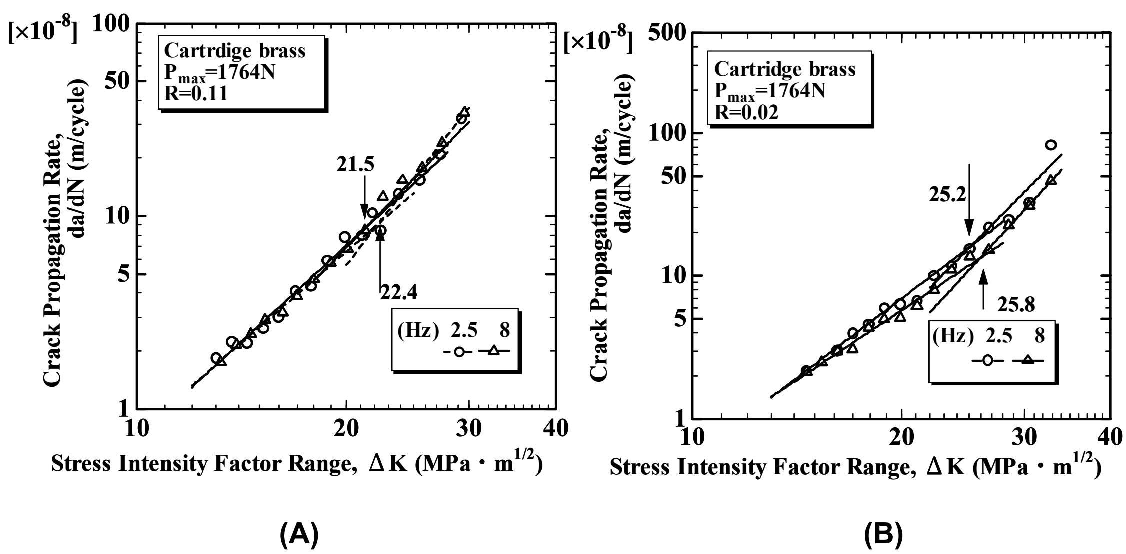


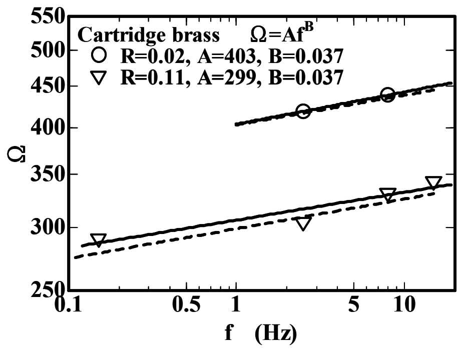
Fig. 3 The transition points at 2.5Hz and 8Hz, (A) with R of 0.11, and (B) with R of 0.02.

The transition phenomenon occurred in the diagram of da/dN vs.ΔK_1. The Transition points of crack growth rate were found out as shown in Fig. 3. The conditions of them are as shown in Table 3. Further, the function Ω was determined by the relationships of Fig.4 and Fig.5, and the above data, as shown in the next function (12), where σ_{ys} is replaced by σ_{fs}=267MPa which is the mean of tensile strength and 0.2% proof stress. Then the coefficient and indexes were obtained as n=428, m=3, B= 0.037. And CTOD, φ_f, was computed as shown in Table 4.

$$\Omega = 428(1-R)^3 f^{0.037} \qquad (12)$$

f (Hz)		0.15	2.5	8	15
ΔK_t (MPa・$m^{1/2}$)	r=0.11	21	21.5	22.4	22.8
	r=0.02		25.2	25.8	

Table 3: The conditions on transition point



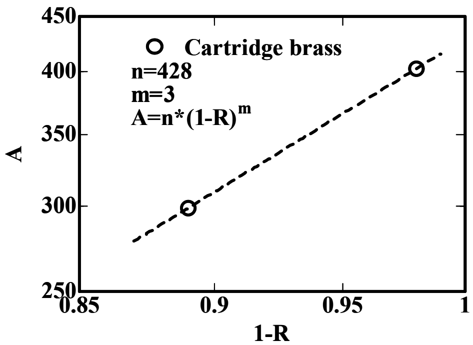


Fig.4 Relation of Ω and f at different R. Fig.5 Coefficient A versus 1-R.

R	f Hz	a mm	ΔK MPa	φ_f μm	Striation μm	Φ_{SEM} μm
0.02	2.5	17	16.16	0.37	0.22	0.42
0.02	8	17	16.16	0.35	0.2	-

Table 4: Fatigue test conditions and data on crack growth

Fracture analysis

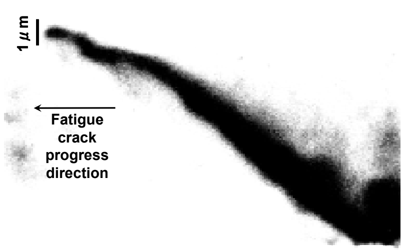
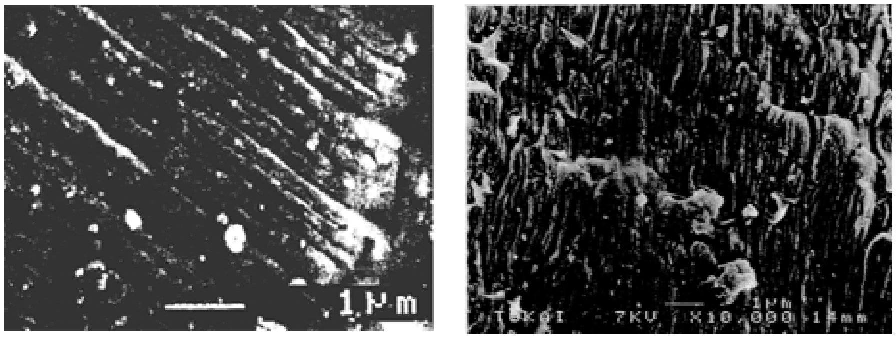


Fig.6 Crack tip at length of crack around 17mm.

The crack tip was examined just as shown in SEM photo as Fig.6, where the fatigue crack was opened statically by setting up the COD with wedge, along the tensile axis, as the same maximum width, 3.23mm, as in fatigue test with f at 2.5Hz and R at 0.02. In the figure, CTOD was detected as 0.42μm which is almost the same as computed data of 0.37μm as shown in Table 4. Next, the striation on the fracture surface of the same test condition was examined by SEM near the same place at crack length of 17mm. As a result, the interval of striation spaces was detected about 0.2μm which is just around one half of computed CTOD, 0.37μm. These results ensured quantitatively the computed CTOD value. From the animation of video microscope, the crack observed microscopically advances zigzag in the space of three dimensions, depending on the crystal organization, and it was considered to be a cause to make the length of CTOD different.



(A) f=2.5Hz **(B) f=8Hz**

Fig.7 Striations formed on fatigue fracture surface of cartridge brass with R of 0.02.

CONCLUSIONS

In the study, the integrated formula for predicting CTOD was guided theoretically and empirically. And its accuracy was identified by several empirical data. As a result, the predicted value of CTOD, φ_f, was obtained approximately equal to the examined CTOD in SEM photo, φ_{SEM}, and near to the double of interval of striation spaces. However, A little difference between them is thought to be caused by zigzag progress of fatigue crack, which is effected by microstructure and shear deformation of plasticity.

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