

CRACK OPENING BEHAVIOR IN ALUMINUM ALLOY 5083

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ABSTRACT

Fatigue life is the summation of crack initiation life and propagation life, but the technique to evaluate initiation and propagation of the crack by a unified theorem has not been established yet. Toyosada et al. proposed a fatigue crack propagation law based on re-tensile plastic zone's generated load (RPG load). Moreover, they established a simulation code for analyzing fatigue crack propagation behavior in various aluminum alloys. An investigation is necessary to check the crack opening behavior in case of both experiment and simulation for each aluminum alloy, before conducting estimation of fatigue crack propagation behavior in aluminum alloys. In this study, the crack opening profiles in aluminum alloy 5083 were estimated by Dugdale Model and these profiles were compared with those by experiments and FEM subject to CCT specimen and a coefficient, called plastic constraint factor was introduced, which should be applied to Dugdale Model to achieve improved crack opening profile in aluminum alloy.

INTRODUCTION

Elber [1] pointed out that fatigue cracks remain closed during the part of load cycle under fatigue loading and proposed effective stress intensity factor ΔK_{eff} which corresponds to the period in which the crack remains open for fatigue crack propagation rate. The effects of stress ratio and spike load on fatigue crack propagation rate could be quantitatively assessed by ΔK_{eff} . However, there is a contradiction that fatigue crack propagates even below threshold value of ΔK_{eff} i.e. $(\Delta K_{eff})_{th}$ under the two step alternating constant amplitude loading [2].

Toyosada et al. [3] considered that fatigue damage does not store up at the crack tip if tensile and compressive plastic zones do not appear in one cycle of repeated loading. Based on this consideration, they proposed that there should be a parameter of fatigue crack propagation rate that is stress intensity factor range ΔK_{RP} which corresponds to the load amplitude from the load when tensile plastic zone appears (re-tensile plastic zone's generated load, RPG load) to the maximum load during loading process. Then, a system that measures RPG load has been developed [4].

It is clarified after performing fatigue crack propagation test subject to constant load amplitude with various stress ratios by using this system that the effect of stress ratio can be quantified. Moreover, they developed a program for analysis of fatigue crack propagation, by which simulation of closure behavior of through-thickness cracks is possible, and this can be estimated by only calculating RPG load. They also verified the ability of this simulation code in the case of steels used as welding structures by comparing with experimental results.

Recently [5, 6, 7] they are accomplishing their research to verify validity of simulation for estimating fatigue crack propagation behavior in various metals, e.g. aluminum alloy. For this purpose, investigation is necessary to verify the crack opening profiles in case of both simulation and experiment for each aluminum alloy.

The crack opening profiles in aluminum alloy 5083 are estimated here by Dugdale Model, finite element method (FEM) and by laboratory experiment. Then a comparison study is conducted with these profiles subject to CCT (Center cracked tension) specimen. A coefficient, called 'plastic constraint factor (pcf)' is then introduced, which is applied to Dugdale Model for the improved crack opening profile in aluminum alloy 5083.

MATERIAL PROPERTIES AND SPECIMEN CONFIGURATION

In the present study, aluminum alloy 5083 is selected by considering the importance of this material in various marine, auto, aircraft and other applications for its light weight on strength basis, good corrosion resistance, etc. Round bar tensile test is performed with this alloy in order to achieve the values of Young's modulus, yield stress, stress hardening coefficient, etc which are used in the calculations of Dugdale Model and finite element analysis. CCT specimen made of aluminum alloy 5083 is used in the experiment, calculation by Dugdale Model and in the finite element analysis. Table 1 shows the chemical composition of this material.

Table 1. Chemical composition of the specimen

Metal	%
Si	0.15
Fe	0.21
Cu	0.02
Mn	0.71
Mg	4.60
Cr	0.11
Zn	0.01
Ti	0.02
Other	Max. 0.15
Al	Rem.

ESTIMATION OF CRACK OPENING PROFILES

By Dugdale Model

Paris [8] stated that the through-thickness crack in deformed condition at mode I, for concentrated load, can be expressed by:

$$V(x_i) = \frac{2}{E'} \int_0^a g(x, a) g(x_i, a) da = f(x_i, x, a) \quad (1)$$

where, the stress intensity factor $K = g(x, a)$, and the crack opening displacement (COD) at $x = x_i$.

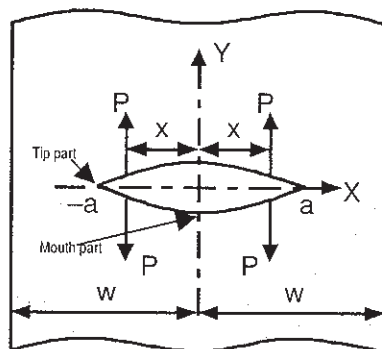


Figure 1 Configuration of CCT specimen

Applying Eq.(1) and from the following equation by Tada et al. [9], which expresses K when the concentrated load of mode I acts on the crack surface of a CCT specimen (Fig.1):

$$K = \frac{2P}{\sqrt{2w}} \sqrt{\tan \frac{\pi a}{2w}} \frac{G\left(\frac{x}{a}, \frac{a}{w}\right)}{\sqrt{1 - \left\{ \frac{\cos(\pi a / 2w)}{\cos(\pi x / 2w)} \right\}^2}} \quad (2)$$

$$\text{where, } G(\chi, \alpha) = 1 + 0.297 \sqrt{1 - \chi^2} \left(1 - \cos \frac{\pi \alpha}{2} \right)$$

COD at $V(x)$ at $x = x$, when a concentrated load P_i acts on the position of $x = x_i$, can be written as follows:

$$V(x) = \frac{4P_i}{E'} \int_0^a \left(\tan \frac{\pi a}{2w} \right) \frac{G\left(\frac{x_i}{a}, \frac{a}{w}\right) G\left(\frac{x}{a}, \frac{a}{w}\right)}{w \sqrt{1 - \left\{ \frac{\cos(\pi a / 2w)}{\cos(\pi x_i / 2w)} \right\}^2} \sqrt{1 - \left\{ \frac{\cos(\pi a / 2w)}{\cos(\pi x / 2w)} \right\}^2}} da \quad (3)$$

COD has been estimated by Dugdale Model, a famous crack opening type coherence model by Dugdale [10], when unit concentrated load acts on each crack surface

position of $x/a = 0, 0.0125, \dots$ subject to CCT specimen for $a/w = 0.3, 0.5$ and 0.7 (i.e. uniform stress distribution with various applied stresses) from Eq.(3).

By Finite Element Method

In this study with FEM, a preprocessor called FEMAP (Finite Element Modeling and Postprocessing) is used to create a model, which is equivalent to the CCT specimen. The properties of the material are input, which are same for the actual data of aluminum alloy 5083. Then, the model is discretized by following the way for acquiring better results. Boundary conditions are applied to the model so that the results subject to displacements can be achieved in case of the same model as during calculations by Dugdale Model, such as $a/w = 0.3, 0.5$ and 0.7 . Loading condition is also set up for same as Dugdale Model, as remote uniform tensile stress distribution. For analysis of the model, FINAS (Finite Element Nonlinear Structural Analysis System) is used to achieve the results subject to displacements in each case of $a/w = 0.3, 0.5$ and 0.7 in various loading steps.

By Experiment

The experiments are performed with CCT specimen (240mm x 100mm x 8mm) of aluminum alloy 5083. The mechanical notches are inserted at the center of the specimen in three different cases as $a/w = 0.3, 0.5$ and 0.7 . COD are measured in various uniform tensile loading steps in three cases of a/w . Considering the importance of the displacement data, experimental investigation is performed at the crack tip neighborhood and mouth part of the crack.

COMPARISON STUDY

In the comparison study, results obtained by Dugdale Model, FEM and experiments are compared to investigate and analyze the crack opening behavior of aluminum alloy 5083 in the case of CCT specimen. Figures 2, 3 and 4 show the results subject to crack opening profiles in various cases of a/w , by Dugdale Model, FEM and experiment, at similar loading steps.

It is found that experimental results almost agree to other results obtained by Dugdale Model and FEM at mouth part of the crack, but differ at tip part. Because, Dugdale Model uses a concept of the virtual crack that differs from the actual crack and FEM presents approximation, whose output at tip part depends on mesh size near crack tip. However, it is recognized that the results estimated by FEM show better crack opening profiles than those by experiments as well as by Dugdale Model. Results subject to COD estimated by Dugdale Model show larger profiles than those by FEM. It is understood from figures that Dugdale Model presents larger COD than actual one and we can refer the results obtained by FEM as more accurate than those by Dugdale Model, although accuracy of the results near the crack tip by FEM depends on discretization technique. Therefore, it should be better to search a way to develop the method subject to Dugdale Model.

In this study, the crack opening profiles estimated by FEM have been considered as reference. Then, a coefficient, called plastic constraint factor, has been introduced in

case of calculating the crack opening displacement profile by Dugdale Model for improved results which match with the results by FEM.

PLASTIC CONSTRAINT FACTOR

The ratio of effective yield stress to general yield stress is called plastic constraint factor, λ . Before suggesting its candidates, the plastic constraint factor in each loading step is calculated so that the profile estimated by Dugdale Model matches with the respective profile estimated by FEM, at both cases of mouth and tip parts of the crack. Figure 5 shows the plastic constraint factors needed for various loading (net stress) steps for $a/w = 0.3, 0.5$ and 0.7 .

It is understood that it is necessary to propose a constant factor as plastic constraint factor by aiming at both mouth and tip parts of the crack. Here, two reasonable candidates for plastic constraint factor are presented.

First and second candidates for plastic constraint factor as $\lambda = 1.061$ and $\lambda = 1.832$ are proposed by considering best average matching of crack opening profile at the mouth part and tip part [at the crack tip opening displacement (CTOD) position] of the crack respectively, in each loading step estimated by Dugdale Model with the respective profile estimated by FEM.

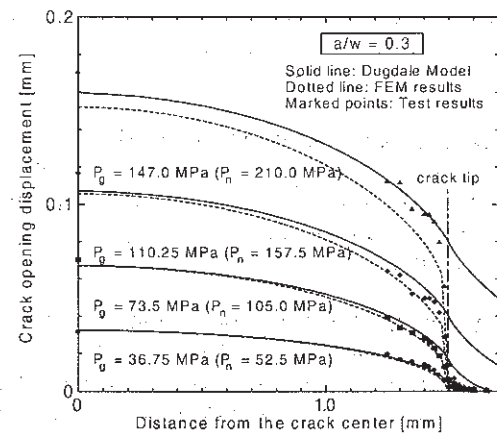


Figure 2 Comparing the crack opening profiles in case of $a/w = 0.3$

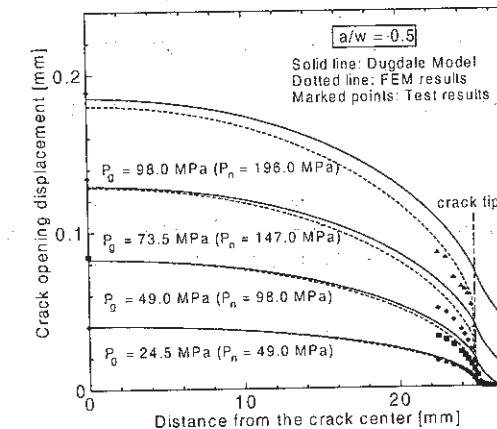


Figure 3 Comparing the crack opening profiles in case of $a/w = 0.5$

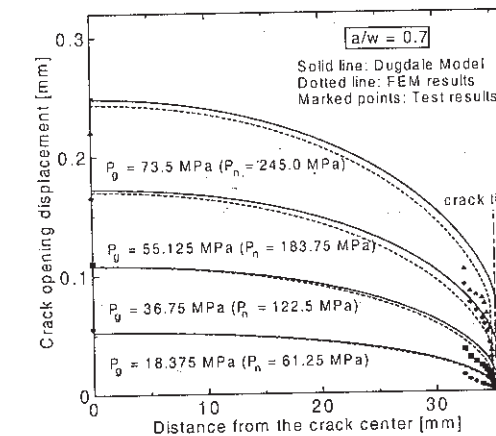


Figure 4 Comparing the crack opening profiles in case of $a/w = 0.7$

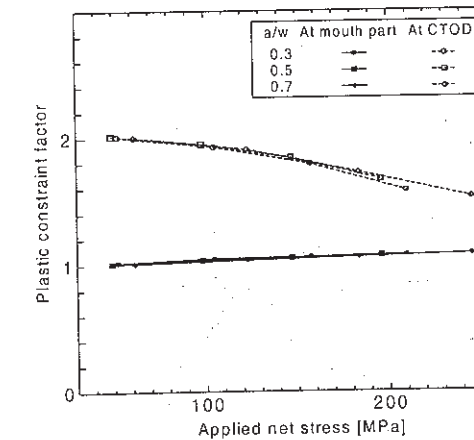


Figure 5 Relation between plastic constraint factor and applied net stress

Figures 6, 7 and 8 show the comparison among crack opening profiles by Dugdale Model, FEM and experiment for $a/w = 0.3, 0.5$ and 0.7 respectively, where estimation by Dugdale Model is performed by using first candidate for plastic constraint factor. These three figures show reasonable improvement in the profiles, especially at the mouth part of the crack.

Figures 9, 10 and 11 show the comparison among crack opening profiles by Dugdale Model, FEM and experiment for $a/w = 0.3, 0.5$ and 0.7 respectively, where estimation by Dugdale Model is performed by using second candidate for plastic constraint factor.

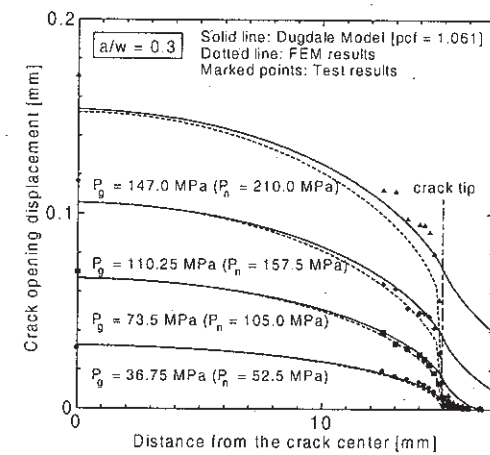


Figure 6 Comparison of crack opening profiles in $a/w = 0.3$, estimated by Dugdale Model, FEM and experiment, where Dugdale Model used first candidate for pcf

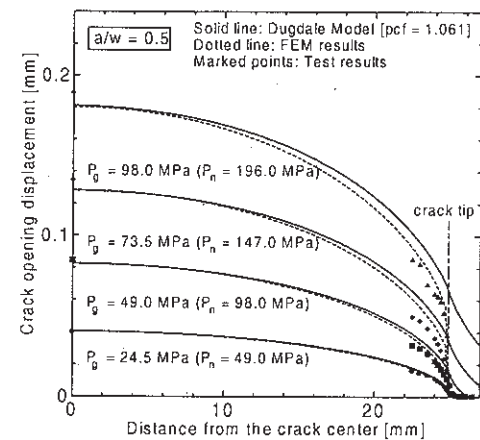


Figure 7 Comparison of crack opening profiles in $a/w = 0.5$, estimated by Dugdale Model, FEM and experiment, where Dugdale Model used first candidate for pcf

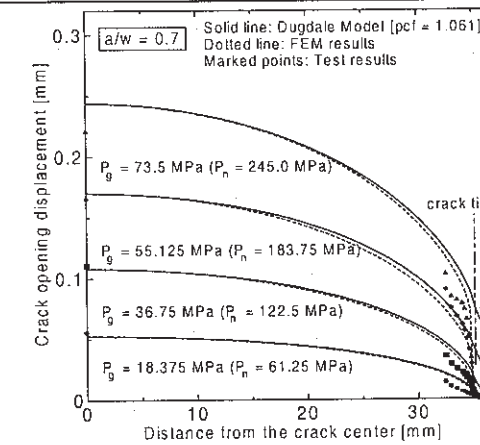


Figure 8 Comparison of crack opening profiles in $a/w = 0.7$, estimated by Dugdale Model, FEM and experiment, where Dugdale Model used first candidate for pcf

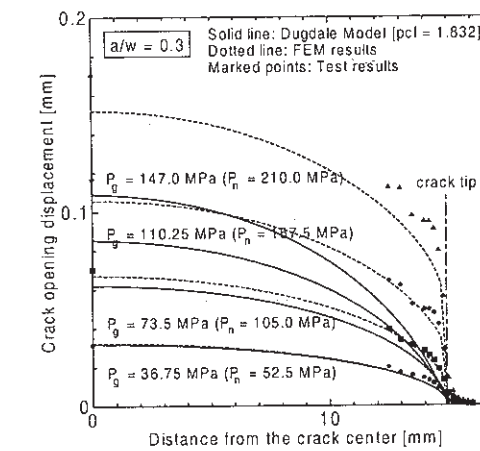


Figure 9 Comparison of crack opening profiles in $a/w = 0.3$, estimated by Dugdale Model, FEM and experiment, where Dugdale Model used second candidate for pcf

CONCLUSION

For the purpose of investigating crack opening behavior of aluminum alloy 5083 subject to CCT specimen, crack opening profiles were estimated by Dugdale Model, FEM and experiment and a comparison study was conducted. The comparison study presents the following conclusion:

It is understood that Dugdale Model presents larger COD than the actual one.

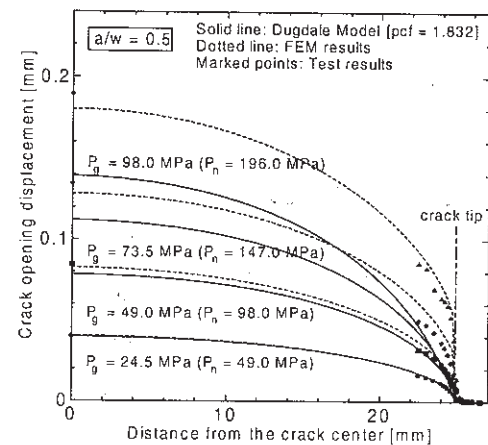


Figure 10 Comparison of crack opening profiles in $a/w = 0.5$, estimated by Dugdale Model, FEM and experiment, where Dugdale Model used second candidate for pcf

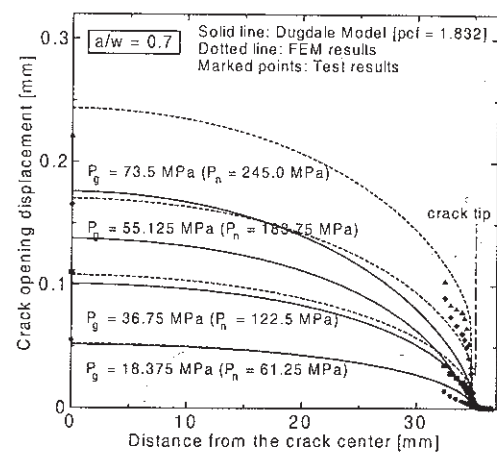


Figure 11 Comparison of crack opening profiles in $a/w = 0.7$, estimated by Dugdale Model, FEM and experiment, where Dugdale Model used second candidate for pcf

The crack opening profiles estimated by finite element method (FEM) present better results.

The experimental results almost agree to the other results obtained by Dugdale Model as well as FEM at the mouth part of the crack, but differ at the tip part. Because, Dugdale Model uses a concept of the virtual crack which differs from the actual crack and FEM presents approximation by analysis, whose output at the tip part depends on the mesh size near the crack tip.

The estimation method of the crack opening profile in aluminum alloy 5083 regarding CCT specimen, by Dugdale Model can be improved by utilizing plastic constraint factor during the calculation by this model. Two reasonable candidates for plastic constraint factor have been presented by aiming at both mouth part and tip part of the crack. Between them, $\lambda = 1.061$ can be proposed as most suitable candidate, since results subject to crack opening displacements at mouth part of the crack estimated by FEM, are more reliable than those at the crack tip neighborhood. Because, results at crack tip neighborhood estimated by FEM differ according to mesh size near that part.

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