STUDY ON PROPAGATION LAW OF SURFACE FATIGUE CRACK AT NOTCH ROOT IN LOW CYCLE FATIGUE UNDER IN-PLANE BENDING

K. Shingai, Y. Yosii, D. Fukui

Department of Mechanical Systems Engineering, Faculty of Engineering, Nagasaki University,
1-14 Bunkyoumachi Nagasaki, 852-8521, JAPAN

ABSTRACT

The fatigue test of the surface crack propagation was conducted on the plate specimen with a small hole at a notch root in the low cycle fatigue region under the reversed deflection control of the in-plane bending load. The surface fatigue crack occurs from a small hole of a notch root center and propagates along a notch root toward both edges of the plate thickness. Cyclic strains at a notch were measured by strain gages and the cyclic strain behavior has been shown as the relationship between the strain and the number of cycle. The strain range at a notch root remains constant as the number of cycle increases, but the mean strain at a notch root increases as the number of cycle increases. It is found that the propagation rate of a surface fatigue crack is expressed as the mth power of the range of the strain intensity factor. The strain intensity factor is defined as the parameter multiplied the strain range at a notch root by root of the half length of a surface crack length. The value of m is 2 in the center and is more than 2 in the edge of the plate thickness. This propagation law of a surface crack can be applied to any radius of notch roots.

KEYWORDS

Surface Fatigue Crack at Notch, Strain Intensity Factor, Propagation Law of Surface Fatigue Crack, Low Cycle Fatigue, Large elastic-plastic strain

INTRODUCTION

The fatigue life of structures and machine parts in the low cycle fatigue region are determined by the initiation life and the propagation life of surface fatigue cracks at notch roots. In case of larger strain range, the main life of the fatigue life becomes the propagation life of the surface fatigue crack. Therefore, we need the propagation law of the surface fatigue crack at a notch root under the large elastic-plastic cyclic strain.

Generally, in case of a small scale yield in front of a crack, the propagation law of the fatigue crack is expressed as the mth power of the range of the stress intensity factor in the linear fracture mechanics as everybody knows [1],[2],[3]. In case of large elastic-plastic state in front of a crack, the propagation rate of a fatigue crack is related to the range of J-integral[4],[5], COD range and the strain intensity factor range [6],[7],[8]. These propagation laws have been obtained usually from tests of the through thickness crack of a plate and a tube etc..

Recently, authors have investigated the cyclic strain behavior of notched specimens under the cyclic in-plane bending load by using strain gages [9],[10]. From results of these studies in low cycle fatigue region, we have found that the cyclic creep occurs at a notch and Coffin-Manson rule is applied to the relationship between the strain range at a notch root and the number of cycles to the initiation of a surface fatigue crack . We should investigate further the propagation law of the surface fatigue crack at a notch root. But up to now, the propagation law of a surface crack at a notch root has been seldom presented. This cause is that the linear fracture mechanics can not be applied to this kind of crack and the cyclic large strain behavior at a notch root is not understood.

In this study we conducted the propagation test of the surface fatigue crack from a small hole at a notch root center and the strain measurement at a notch by using strain gages under the cyclic in-plane bending load. In this report we present the behavior of the surface fatigue crack, the cyclic strain behavior at a notch and the propagation law of the surface fatigue crack.

MATERIAL, SPECIMEN AND EXPERIMENTAL PROCEDURE

Chemical composition and mechanical properties of the carbon steel annealed are shown in Table 1 and Table 2 respectively. Specimens with notches are shown in Fig.1. A small hole (the diameter of 0.5 mm and the depth of 0.5 mm) is drilled at one notch root center and a strain gage is attached to other notch root. The length of a surface fatigue crack is measured on fine lines drawn on a notch root by the CCD camera. The strain gage with gage length of 0.2 mm is attached to a notch root and strain gages with gage length of 1 mm are attached in front of a notch at distance of 1 or 2 mm. The test have been conducted by the fatigue apparatus of in-plane

TABLE 1

CHEMICAL COMPOSITION(%)

C	Si	Mn	P	S	Ni	Cr	Ca
0.24	0.22	0.50	0.012	0.016	0.07	0.15	0.13

TABLE 2

MECHANICAL PROPERTIES

Modulus of elasticity	199 GPa
Yield stress	273 MPa
Tensile strength	457 MPa
Elongation	38 %

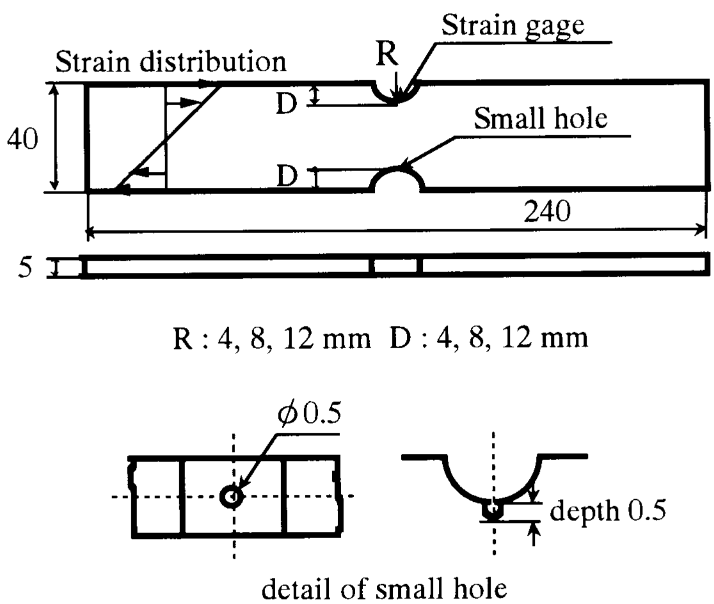


Figure 1 : Specimens with notches

bending with constant deflection control by the eccentric cam and strains have been measured at proper number of cycle using the dynamic strain recorder. Here, the strain distribution by in-plane bending load is shown in a specimen in Fig.1. Experimental conditions are the room temperature, the reversed control of in-plane bending deflection and 72 cpm of the frequency. Test condition of each specimen is shown in Table 3. R is a notch radius. C2, C3 etc. are cam number and the displacement control of the in-plane bending load is determined by cam number. ε_R is the strain range at a notch root measured by a strain gage.

TABLE 3

TEST CONDITION OF EACH SPECIMEN

Notch root radius R (mm)	Cam No	Strain range measured ε_R (%)
R8	C2	3.05
R8	C4	1.03
R8	C5	0.45
R4	C3	1.60
R12	C2	1.70

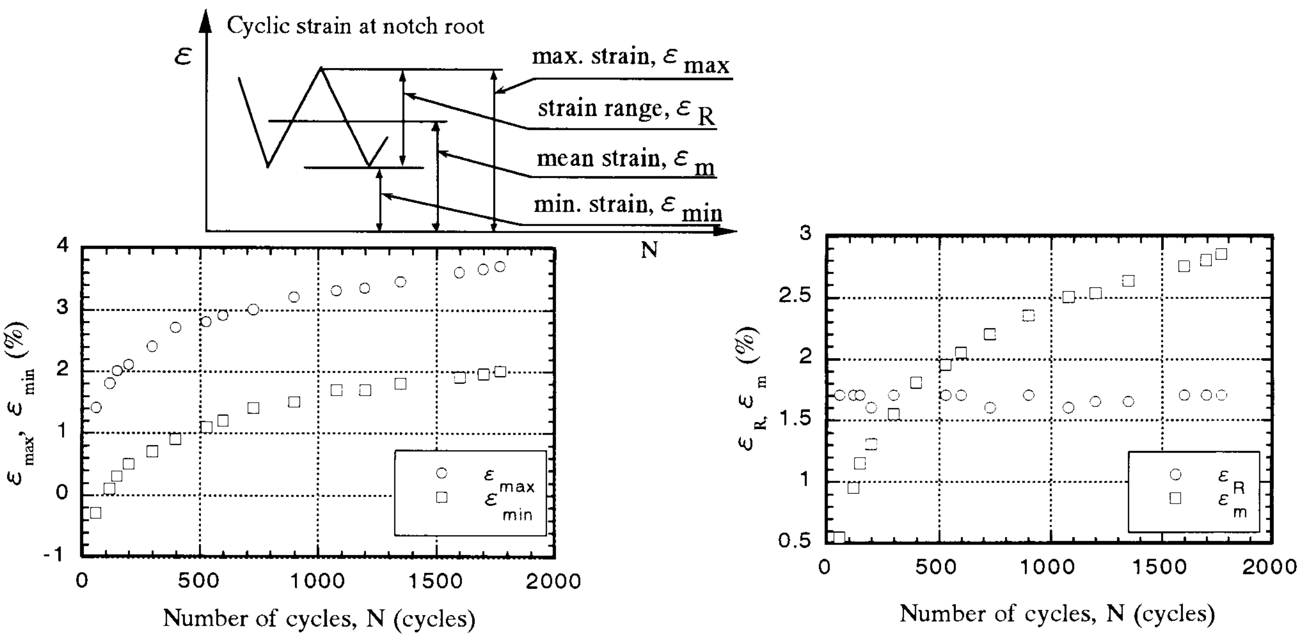
EXPERIMENTAL RESULTS AND DISCUSSIONS

CYCLIC STRAIN BEHAVIOR AT NOTCH

Fig.2.a shows the relationship between the maximum strain, the minimum strain at a notch root and the number of cycle, and Fig.2.b shows the relationship between the strain range, the mean strain at a notch root and the number of cycle. The cyclic creep occurs at a notch root and strains increases toward the tension as the number of cycle increases. The strain range remains constant during cyclic loading, but the mean strain increases as the number of cycle increases. From this result, we think that the surface fatigue crack at a notch root opens during the reversed in-plane bending. Therefore, we think that the full range of the strain intensity factor is useful to the propagation of the surface fatigue crack in the propagation law of the crack in equation (1) mentioned later.

Fig. 3 shows the changes of the strain distribution at 10 cycles and at 100 cycles. It is found that the strain distribution changes drastically as the number of cycle increases.

From these results, it is found that the cyclic strain behavior at a notch shows the complex behavior.



a. ε_{max}, ε_{min} vs N   b. ε_R, ε_m vs N

Figure 2 : ε_{max}, ε_{min}, ε_R, ε_m vs N

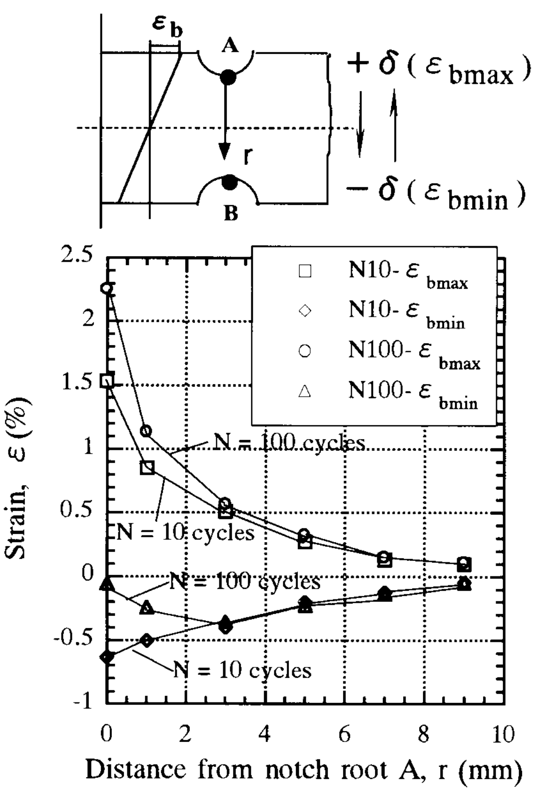


Figure 3 : Change of strain distribution

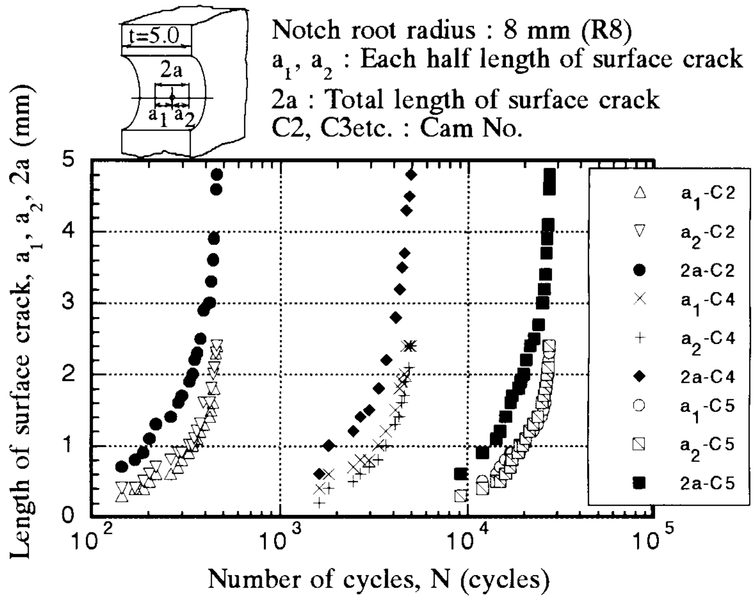


Figure 4 : Relatonship between surface crack length and number of cycles

PROPAGATION LAW OF SURFACE FATIGUE CRACK AT NOTCH ROOT

Fig. 4 shows the relationship between the length of a surface fatigue crack and the number of cycle.

Fig. 5 shows the propagation path model of the surface fatigue crack at a notch root. The region A is the typical surface crack in the center part of the plate thickness and the region B is the surface crack influenced by the edge of the plate thickness.

Fig. 6 shows the relationship between the propagation rate of the surface fatigue crack and the half crack

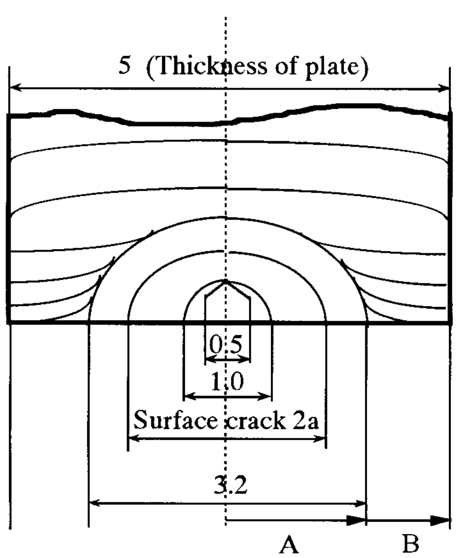


Figure 5 : Path model of surface fatigue crack

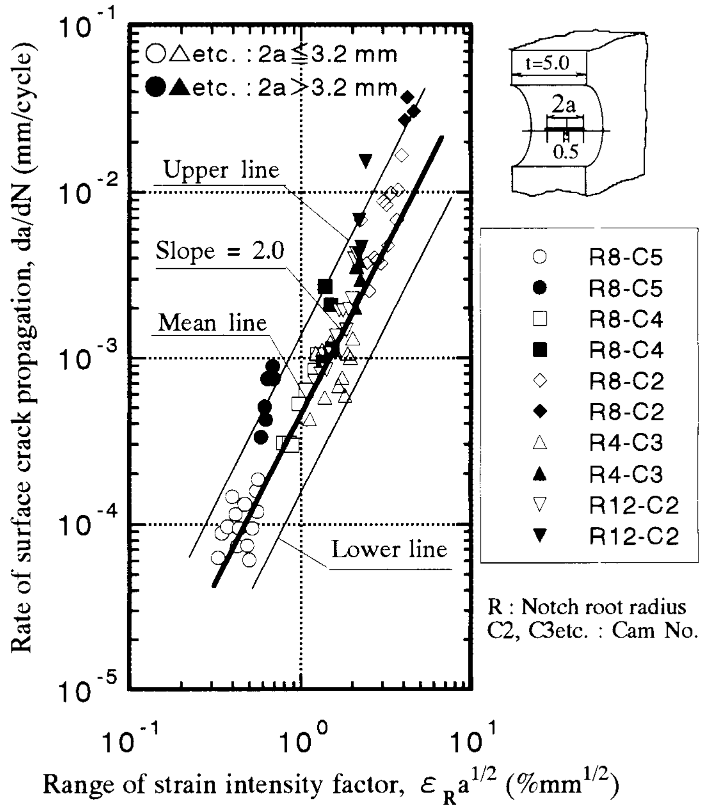


Figure 6 : Relationship between rate of surface fatigue crack propagation and range of strain intensity factor

length. The propagation rate of a crack in the center of the plate thickness is proportional to the half crack length because the slope is 1.0 in a smaller crack than 3.2 mm of a crack length. But one in the edge of the plate thickness is not proportional to the half crack length because the slope is larger than 1.0 in a larger crack than 3.2 mm of a crack length. The reason of regions A and B in Fig. 5 is due to this matter.

Fig. 7 shows the relationship between the propagation rate of a surface fatigue crack and the range of the strain intensity factor. The strain intensity factor is defined as the parameter multiplied the strain range at a notch root by root of the half length of a surface crack length. It is found that the propagation rate of a surface fatigue crack is expressed as the 2nd. power of the range of strain intensity factor in white mark data in the region A. This experimental equation in the region A is expressed as Eq. (1) as follows :

$$da/dN = C\,(\varepsilon_R\, a^{1/2})^2 \qquad (1)$$

da/dN : the propagation rate of a surface fatigue crack (mm/cycle)
C : the material constant
ε_R : the strain range at a notch root (%)
a : the half crack length of a surface fatigue crack (mm)
$\varepsilon_R\, a^{1/2}$: the range of the strain intensity factor (% $mm^{1/2}$)

The slope in black mark data of the region B is larger than 1.0 in the region A and the propagation rate in the region B is higher than one in the region A. This law can be applied to any notch radius because the data obtained from 4, 8, 12 mm of notch radiuses is within the scattered band.

Fig. 8 shows the elastic-plastic state of the surface crack at a notch root. The elastic-plastic strain is cycled at a notch root and the plastic zone extends in front of a notch. The high strain at a surface crack is composed of the strain concentration by a notch and the strain concentration by a crack. The linear fracture mechanics can

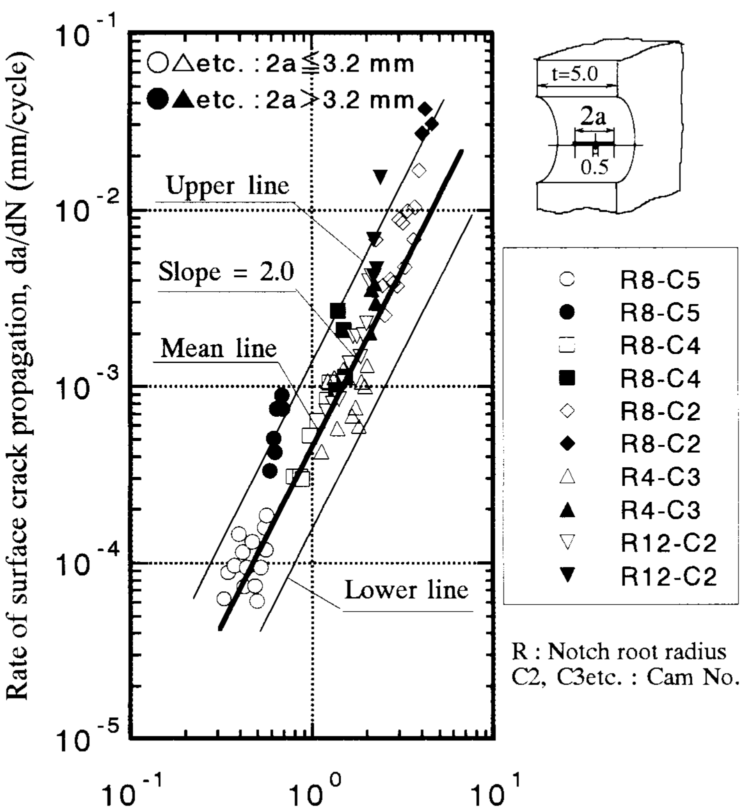


Figure 7 : Relationship between rate of surface fatigue crack propagation and range of strain intensity factor

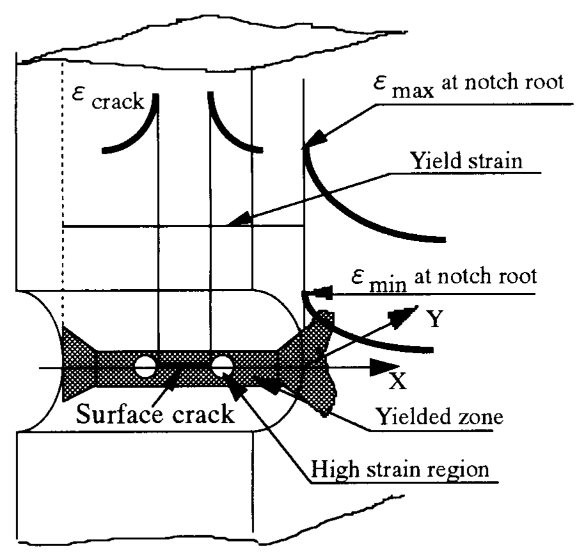


Figure 8 : Strain state of surface crack at notch root

not be applied to this crack. The author thinks that the strain intensity factor defined in this paper can be applied to this crack. The strain intensity factor is equivalent to the stress intensity factor in case of the small scale yield in the linear fracture mechanics. Therefore, the strain intensity factor can be applied to a crack from the state of the small scale yield to one of the large scale yield.

Authors [6] have shown already that the strain intensity factor similar to one in this paper has been applied to the through edge crack propagation of a plate specimen under the control of the bending angle of in-plane bending. Therefore, the strain intensity factor can be applied to the propagation of a surface crack at a notch root and one of a through edge crack for the plate specimen.

This propagation law of a surface crack at a notch root may be applied to the estimation of surface crack propagation of the real structures with notches, because strains at notch roots in the real structures can be measured easily by strain gages and can be calculated by the finite element method etc..

CONCLUSIONS

1. The propagation rate of a surface fatigue crack at a notch root is expressed as the mth power of the range of strain intensity factor. The strain intensity factor is defined as the parameter multiplied the strain range at a notch root by root of the half length of a surface crack length. The value of m is 2 in the center and is more than 2 in the edge of the plate thickness. This propagation law of a surface crack can be applied to any radius of notch roots.
2. The cyclic creep occurs at a notch root and strains increases toward the tension as the number of cycle increases. The strain range remains constant during cyclic loading, but the mean strain increases as the number of cycle increases. The strain distribution changes drastically as the number of cycle increases. From these results, it is found that the cyclic strain behavior at a notch shows the complex behavior.

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