CRACK GROWTH AND THRESHOLD CHARACTERISTICS OF SURFACE FATIGUE CRACK IN PLATE SPECIMEN OF 0.45% CARBON STEEL *

A.Washida **, E.Tsuchida *** and H.Kobayashi ****

Crack growth, threshold and closure characteristics of surface fatigue cracks were examined, using surface notched plate specimens of a 0.45% Carbon steel with different grain sizes in air and at room temperature.

The results obtained are summarized as follows:

- (1) In the case of constant load range tests, the aspect ratio of a surface crack decreases with flattening of the crack shape as the crack grows, because the bending stress component increases with a decreasing ligament of the specimen.
- (2) The grain size influences the crack growth rate and the aspect ratio.
- (3) In the case of decreasing load range tests, the values of threshold ΔK_{th} in the depth direction are about 8 and 4% higher than those at the surface, in the cases of fine and coarse grain size, respectively. This is caused by flattening of the crack shape. The grain size influences strongly the threshold characteristic. In both directions, ΔK_{th} of a specimen having coarse grain size is about 40% higher than that of a specimen having fine grain size.

Key Words : Fatigue, Surface Crack, Crack Growth Rate, Stress Intensity Factor Range, Crack Closure, Threshold

1. Introduction

Fatigue crack growth characteristics of a through crack have been studied and made clear on various materials and environments ⁽¹⁾⁻⁽⁴⁾. Up to now the assessments of cracks in structures are mainly based on the data on through cracks.

The cracks contained in structures, however, are mostly 3-dimensional surface or embedded cracks. So, it is not enough to assess them by using only the data on through cracks. It is important to make clear the crack growth and threshold characteristics of the surface fatigue crack in order to prevent the fatigue failure of the structures. Recently the growth characteristics of the surface fatigue crack have come to be studied ⁽⁵⁾⁻⁽⁸⁾, but the threshold characteristics are not studied so much ^{(7),(8)}.

In this study, the crack growth, threshold and closure characteristics of the surface fatigue crack are examined by the constant load range and decreasing load range tests, using surface notched plate specimens of a 0.45% Carbon steel with different grain sizes in air and at room temperature.

2. Experimental Procedure

The material used is a 0.45% Carbon steel (JIS S45C) and its chemical composition is shown in Table 1. The shapes of the specimen and surface notches are shown in Fig.1. The surface notch was made by an electro-discharge machining at the center of one surface of the specimen.

After machining, the following two types of annealing were conducted in a vacuum and two types of grain sizes were obtained.

- (A) Keeping specimens at 850°C for one hour and then cooling down in a vacuum.
- (B) Keeping specimens at 850°C for 24 hours and then cooling down in a vacuum. Mechanical properties and grain sizes after the annealing are shown in Table 2.

Fatigue tests were done by MTS fatigue testing machine (load capacity ± 245 kN) with the load controlled in air and at room temperature. Load conditions are as follows. The waveform is sinusoidal, the stress ratio $R=0$, and the frequencies are ranged from 3 Hz to 8 Hz. Constant-load range ΔP and decreasing- ΔP (decreasing rate : 7.5%-15%) fatigue tests were conducted in order to study the crack growth and threshold characteristics. In the latter case, the test is continued under the constant ΔP condition after the threshold condition is achieved. The definition of crack sizes is shown in Fig.2. The surface crack length $2b$ was measured directly by a traveling microscope and the crack depth a was measured by using beach marks placed on the fracture surface.

The crack opening loads P_o were measured by changes of the outputs from strain gages near the crack at the

* Received 30th September, 1983.

** Post Graduate Student, University of Tokyo, 7-8-1 Hongo, Bunkyo, Tokyo, 113 Japan.

*** Professor, Saitama University, 255 Shimo-okubo, Urawa, Saitama, 338 Japan.

**** Associate Professor, Tokyo Institute of Technology, Ohokayama, Meguro, Tokyo, 152 Japan.

surface and on the back face of a specimen by the unloading elastic compliance method ^{(9),(10)}. In measuring P_{op} , the frequency was lowered to 0.05Hz-0.1Hz. The locations of strain gages are shown in Fig.3.

3. Experimental Results and Discussion

In this paper, S and L denote a fine and a coarse grain size, and subscripts B and A denote a surface and a depth direction, respectively.

3.1 Constant- ΔP Fatigue Test

3.1.1 Crack Growth Characteristics of Surface Fatigue Cracks

Macroscopic photographs of the

Fig.1 Specimen geometry and shapes of surface notches

Fig.2 Definition of crack length

fracture surfaces are shown in Fig.4. The relations between the aspect ratio of the surface crack, a/b , and the ratio of the crack depth to the specimen thickness, a/t , is shown in Fig.5. The value of a/b changed toward 1.0, although it was influenced by the surface notch in the early stage of crack growth. After a/b was nearly equal 1.0, settled to $a/b \approx 1.0$ (semicircular), decreased with flattening of the crack shape as the crack grew, the

Fig.3 Locations of strain gages (crack closure measurement)

Fig.4 Macroscopic features of fracture surfaces

Table 1 Chemical composition (wt.%)

C	Si	Mn	P	S	Cu	Cr
0.46	0.19	0.70	0.03	0.009	0.01	0.06

Table 2 Yield stress and grain size after annealing

	Yield stress (MPa)	Average grain size (mm)	Grain size number
Anneal A	355	0.012	10
Anneal B	336	0.025	8

specimen was finally broken. The tendency of surface crack's flattening is in agreement with the results of the others (6), (7).

The reason for crack's flattening may be due to the bending stress acting on the ligament of the specimen. Though a uniform tensile load acted on the ends of the specimen, the bending stress component increased with a decreasing ligament of it. The method of measuring the bending stress component using another same shape specimen and its results are shown in Figs. 6 and 7, respectively. In Fig. 7, the vertical axis represents the ratio of the back face strain to the front face strain, $\epsilon_{Bmax}/\epsilon_{Fmax}$, and the horizontal one does a/t . The subscripts B and F represent the back face and the front face, respectively. When $\epsilon_{Bmax}/\epsilon_{Fmax}$ becomes less than 1.0, the values of a/t are more than 0.4. This tendency agrees with the fact that the crack becomes flat when a/t is more than 0.4.

The relations between db/dN and ΔK_B and between da/dN and ΔK_A are shown in Figs. 8 and 9, respectively, where db/dN and da/dN are the crack growth rates at the surface and that in the depth direction of a specimen, respectively, and ΔK_B and ΔK_A are the stress intensity factor ranges corresponding to db/dN and da/dN , respectively. ΔK was calculated by the analytical results of Kobayashi⁽¹¹⁾ and partly of Raju-Newman⁽¹²⁾. Paris' law holds in Figs. 8 and 9, that is;

$$da/dN = C\Delta K^m \quad (1)$$

The open symbols represent specimens having fine grain size and the solid symbols do specimens having coarse grain size. The straight lines were obtained by the method of least squares in double logarithmic plots and the values of m and C are shown in Table 3.

Comparing Fig. 8 with Fig. 9, da/dN is larger than db/dN in the range of low ΔK , but the relation is reversed in the range of high ΔK .

This tendency is remarkable in the case of specimens having fine grain size. These specimens showed more crack's flattening than specimens having coarse grain size.

3.1.2 Influences of Grain Sizes

The influences of grain sizes are shown in Fig. 5. A crack having fine grain size is flatter than one having coarse grain size. The influences of grain sizes are also shown in Figs. 8 and 9. At the surface of a specimen, db/dN of the fine grain size is larger than that of the coarse grain size for the same value of ΔK_B .

In the depth direction, da/dN of the fine grain size is larger than that of the coarse grain size in the range of low ΔK_A , but this relation is reversed in the range of high ΔK_A . The value of ΔK_A at the reversing point nearly agrees with that where the crack becomes flat.

Fig.5 Relations between a/b and a/t

Fig.6 Locations of strain gages (bending stress measurement)

Fig.7 Relations between $\epsilon_{Bmax}/\epsilon_{Fmax}$ and a/t

3.2 Decreasing- ΔP Fatigue Tests

3.2.1 Threshold Characteristics of Surface Fatigue Cracks

Macroscopic photographs of the fracture surface are shown in Fig. 10. The dark red fretting oxide debris adheres to the area from the notch to the crack front, where the crack stops near threshold, and the color becomes dark with an approaching crack front. In this paper, the crack growth threshold means the limit where the crack can no more growth at the surface when a load range of more than 8.5×10^6 cycles acts on the specimen. From observing the fracture surfaces, the following was revealed. In the case of a specimen having fine grain size, the crack did not grow in the depth direction near threshold. In the case of a specimen having coarse grain size, however, the crack grew locally and was arrested during the above mentioned cycles.

The relations between a/b and a/t are shown in Fig. 11. The solid symbols represent the threshold in Fig. 11. The values of a/b decrease suddenly with a decreasing ΔK . This result differs from that shown in Figure 5 and may be caused by a difference in crack closure at the

surface and in the inside of a specimen, i.e. crack closure in the inside is stronger than that at the surface. The relations between db/dN and ΔK_B and between da/dN and ΔK_A are shown in Figs. 12 and 13, respectively. In these figures, the solid lines for the fine grain size (S) and the broken lines for the coarse grain size (L) show the results of the constant- ΔP tests. The data of No.101 specimen are not adopted because the decreasing rate of ΔP was large and the crack growth rate decreased suddenly. In both directions, i.e., at the surface and in the depth direction, the threshold is distinctly recognized. The values of threshold, ΔK_{th} , are shown in Table 4. The values of threshold in the depth direction, ΔK_{Ath} , are about 8 and 4% higher than those at the surface, ΔK_{Bth} , in the cases of fine and coarse grain size, respectively. This was caused by flattening of the crack shape near threshold. The value of a/b becomes about 0.8 under an assumption that $\Delta K_B = \Delta K_A$. When a/b is less than 0.8, ΔK_A is higher than ΔK_B . In this fatigue tests, a/b is less than 0.8 near threshold, as shown in Fig. 11.

Fig.8 Relations between db/dN and ΔK_B (at surface)

Fig.9 Relations between da/dN and ΔK_A (in depth direction)

Table 3 Values of m and C

	m	C	ΔK range ($\text{MPa}\sqrt{\text{m}}$)
Surface	S	6.55×10^{-15}	$16.0 < \Delta K_B < 35.5$
	L	6.31×10^{-15}	$13.5 < \Delta K_B < 36.0$
Depth	S	3.55×10^{-12}	$15.0 < \Delta K_A < 43.0$
	L	1.56×10^{-13}	$13.5 < \Delta K_A < 40.0$

3.2.2 Effects of Grain Sizes on Threshold Characteristics

Remarkable effects of grain sizes near threshold are seen in Figs. 12 and 13. In Table 4, ΔK_{th} of a specimen having coarse grain size was about 40% higher than that of a specimen having fine grain size in both directions. This may be caused by a difference of crack closure between the coarse and the fine grain sizes. In other words, the fracture surface of the coarse grain size is rougher than that of the fine grain size, and accordingly the roughness promotes the partial contact of the fracture surfaces⁽¹³⁾. As a result, fretting oxide debris are produced between the fracture surfaces, and it causes crack closure. Consequently ΔK_{th} may be high⁽⁴⁾. Therefore, the starting condition of ΔP -decreasing test may influence ΔK_{th} , too⁽¹⁴⁾.

Fig.10 Macroscopic features of fracture surfaces

Fig.11 Relations between a/b and a/t

Fig.12 Relations between db/dN and ΔK_s (at surface)

Fig.13 Relations between da/dN and ΔK_a (in depth direction)

Table 4 Values of ΔK_{th}

	ΔK_{Bth} (MPa $\sqrt{m}$)	ΔK_{Ath} (MPa $\sqrt{m}$)
S	6.33	6.86
L	9.24	9.57

3.2.3 Crack Closure

Examples of measuring the crack opening load, P_{op} , by the unloading elastic compliance method are shown in Fig. 14. The vertical and horizontal axes represent the load P and the result of subtracting the value of aP from the strain ϵ , $(\epsilon - aP)$, respectively, where a is a coefficient. In this paper, it is assumed that the crack opening load P_{op} is equal to the crack closure load P_{cl} . In Fig. 14, arrow marks represent P_{op} . The crack opening load P_{sop} at the surface was measured by strain gages near the crack at the surface and P_{Aop} in the depth direction was measured by strain gages on the back face of a specimen.

Crack opening ratios U_B and U_A are defined by a following equation

$$U = (P_{max} - P_{op}) / (P_{max} - P_{min}) \quad (2)$$

where $P_{op} \geq P_{min}$. The relations between U_B and ΔK_B and between U_A and ΔK_A are shown in Figs. 15 and 16, respectively. Solid symbols represent data near threshold. In Fig. 15, U_B of a coarse grain size is smaller than that of a fine grain size for the same value of ΔK_B in the range of low ΔK_B . This may be caused by a difference of fretting oxide induced crack closure, although there is no clear difference between U_B and U_A . The effective stress intensity factor range ΔK_{eff} is defined by a following equation.

$$\Delta K_{eff} = U \cdot \Delta K \quad (3)$$

The relations between db/dN and $\Delta K_{B_{eff}}$ and between da/dN and $\Delta K_{A_{eff}}$ are shown in Figures 17 and 18, respectively. In both

Fig.14 Examples of measured P_{op} (at surface)

figures, there are clear thresholds for ΔK_{eff} . This result may depend on the technique for measuring P_{op} .

P_{op} of both directions must be measured precisely and separately in the case of the surface crack. But the technique for measuring P_{op} is not established. In this paper, P_{op} of both directions are influenced by crack closure of another direction. In future, it is necessary to study about this.

4. Conclusions

Constant- ΔP and decreasing- ΔP fatigue tests were conducted, using surface notched plate specimens of a 0.45% Carbon steel with different grain sizes in air and at room temperature. Crack growth and threshold characteristics of surface fatigue cracks were examined.

The results obtained are as follows:

- (1) In the case of the constant- ΔP tests, the aspect ratio of a surface crack changes toward 1.0, although it is influenced by a surface notch in the early stage of crack growth. Then, it decreases with flattening of the crack shape as the crack grows, because the bending stress component increases with a decreasing ligament of the specimen.
- (2) Comparing the crack growth rates at the surface and in the depth direction within the ranges where Paris' law holds, the rate in the depth direction is larger than that at the surface of a specimen in the range of low ΔK range, but this relation is reversed in the range of high ΔK . This tendency is remarkable in the case of a specimen having fine grain size that have a flatter crack than in the case of a specimen having coarse grain size.

Fig.15 Relations between U_B and ΔK_B (at surface)

Fig.16 Relations between U_A and ΔK_A (in depth direction)

Fig. 17 Relations between db/dN and ΔK_{Bsurf} (at surface)

Fig. 18 Relations between da/dN and ΔK_{Aeff} (in depth direction)

The grain size influences also the crack growth rate and the aspect ratio.

(3) In the case of the decreasing- ΔP tests, the values of threshold ΔK_{th} in the depth direction are about 8 and 4 % higher than those at the surface, in the cases of fine and coarse grain size. This is caused by flattening of the crack shape. The grain size influences strongly the threshold characteristic. In both directions, ΔK_{th} of a specimen having coarse grain size is about 40% higher than that of a specimen having fine grain size.

References

- (1) Paris, P. C. and Erdogan, F., Trans. ASME, Ser. D, Vol. 85, (1963), p. 528.
- (2) Elber, W., ASTM Spec. Tech. Publ., 486, (1971), p. 230.
- (3) Kikukawa, M., et al., Jour. Soc. Mate. Sci. Japan, Vol. 30, No. 330, (1981-3), (in Japanese).
- (4) Kobayashi, H., Trans. Japan Soc. Mech. Engrs., Vol. 49, No. 443, (1983-7), p. 771, (in Japanese).
- (5) Kasai, K., et al., Preprint of Japan Soc. Mech. Engrs., No. 740-10, (1974-11), p. 211, (in Japanese).
- (6) Kawahara, M. and Kurihara, M., Jour. Soc. Nav. Arch. Japan, No. 137, (1975-6), p. 297, (in Japanese).
- (7) Kitagawa, H. and Takahashi, S., Trans. Japan Soc. Mech. Engrs., Series A, Vol. 45, No. 399, (1979-11), p. 1289, (in Japanese).
- (8) Hoshide, T. and Tanaka, K., Trans. Japan Soc. Mech. Engrs., Series A, Vol. 48, No. 433, (1982-9), p. 1102, (in Japanese).
- (9) Kikukawa, M., et al., Jour. Soc. Mate. Sci. Japan, Vol. 25, No. 276, (1976-9), p. 899, (in Japanese).
- (10) Kawai, S., Trans. Japan Soc. Mech. Engrs., Series A, Vol. 47, No. 421, (1981-9), p. 859, (in Japanese).
- (11) Kobayashi, A. S., Proc. 2nd Int. Conf. Mech. Behavior of Materials, (1976).
- (12) Raju, I. S. and Newman, J. C. Jr., Engng. Fract. Mech. Vol. 11, (1979), p. 817.
- (13) Minakawa, K. and McEvily, A. I., Scripta Met., Vol. 15, (1981), p. 633.
- (14) Asami, K. and Terasawa, M., Preprint of Japan Soc. Mech. Engrs., No. 830-2, (1983-3), p. 117, (in Japanese).