QUANTITATIVE INVESTIGATION OF INITIATION AND EARLY GROWTH PROCESS OF FATIGUE MICROCRACKS IN LOW CARBON STEEL

Yasuo Ochi and Shigemi Sasaki
Department of Mechanical Engineering, University of Electro-Communications, Chofu, Tokyo, Japan

Generally, a fatigue fracture process of metals is preceded by formation of fatigue slip bands(FSB's), and microcracks as results of FSB's growth initiate and propagate to macrocracks[1,2]. The studies in this field is characterized by two parts : the initiation and the propagation of cracks. During the fatigue process of unnotched smooth materials, as FSB's initiate at very early stage and macrocracks at the latest stage, then it is assumed that the most part of the process is occupied by increasing stage of FSB's and microcracks[3]. However, the researches which have treated them quantitatively have apparently been rarely reported[4,5].

In this study, high cycle fatigue tests were performed on smooth bar specimens of low carbon steel. The initiation behavior and the propagation process of FSB's and microcracks were investigated quantitatively from varous observations on a surface, a fracture surface and cross section.

EXPERIMENTAL PROCEDURE

Materials used in this study were three kinds of low carbon steels (0.07%, 0.15% and 0.16% carbon steels). The static mechanical properties after heat treatment are given in Table 1. After test specimens were machined to dimensions of 7, 8 and 11 mm in diameters, the heat treatment in 10^{-5}mmHg vacuum furnace were given at the condition of 930°C for 1 hour. The specimens were finished on the smooth surface after that and were etched on the observation area of the surface. Fatigue testing machines of Ono type and Cantilever type rotating bending with 50 Hz were used.

Optical Microscope(OM, X400) and Transmission Electron Microscope(TEM, X1000-6000) with 2nd stage carbon replica were used for the observation of FSB's. Shapes and initiation angles of surface microcracks were observed by surface polishing technique with OM and by fractographs of fracture surface of cracks with Scanning Electron Microscope(SEM). And, early growth behaviors in direction of depth of cracks were observed on longitudinal cross sections of specimens with OM.

EXPERIMENTAL RESULTS AND DISCUSSION

1. Quantitative Expression of Variations of FSB's

The variations of FSB's during fatigue process were expressed quantitatively as follows,

Volume fraction of FSB's, V_{sf} = (Ratio of FSB's area, A_{sf}) X (Ratio of FSB's depth, h_{sf}) X (Ratio of number of slipped grains, G_{sf}) -------(1)

Explanations of each terms in Eq.(1) should be reffered to the another work [6] for detail. Figure 1 shows an example of variations of FSB's during the process : (a) shows the variations of A_{sf}, (b) h_{sf} and (c) G_{sf}. In the Fig.1 FSB's initiate at the very early stage of the process(N/N_f=1-5%) and increase in their area and the depth with cycling of stress, attaining to fracture, whereas, the G_{sf} tends to saturate in early stage

2. Surface Crack Shapes and Fractographic Investigation

Figure 2 shows an example of crack shapes (the front view and the side view) by the surface polishing technique, (a) shows the shallow stage I crack and (b) the deeper one propagating to stage II. From the figure and other observations, the average depth of stage I cracks was about 20-30 μm and the average initiation angles of the cracks φ of the cracks to the perpendicular of the stress axis was about 43° which agreed approximately with the maximumshear direction.

Figure 3 shows a crack aspect ratio(b/2a) to a ratio of crack depth to specimens diameter(b/D) from the fractographic observation of fracture surface of cracks. In the figure, the values of (b/2a) increased with increasing of (b/D) in the smaller region of (b/D)($\fallingdotseq$ 0.008) , but they were in al-most constant bands at the region above the value of (b/D). Figure 4 shows the distribution of angle of crack initiation and the stress dependence of the average value of the angle. From the figure, it was shown that the distribution was approximately a normal distribution with the maximum division of $\varphi=40\text{-}50^{\circ}$ (a broken curve in the figure(a) shows a comformable normal distribution curve), and the value of φ doesn't depend on σ_a.

3. Early Growth Stage of Microcracks by Cross Sectional Investigation

Schematic representation of the initial growth stage of microcracks in the direction of depth are shown in Fig.5. After the initiation of cracks as continuous process from FSB's, they grow along the slip planes in the grain. When the microcracks collide with some obstacles such as boundaries or perlites, they received the resistance from them and may change easily the direction of the propagation. Therefore, it is assumed that stage I crack depth is about one grain size[2]. Then, as the cracks propagate in the transition region along the crystallographic slip planes, if the composed region of stage I and the transition region of cracks was called as the initiation crack, it is clear that the depth of the initiation crack is about two or three grain sizes. In order to confirm these matter, Fig.6 was obtained as the results of the cross sectional observation. In the figure, (a) shows the distributions of the number of grain boundaries passed by the initiation cracks (including perlites) n, (b) the distributions of the initiation crack depth b_I. From the figure(a), the values of n were distributed with the peak value of one or two grains, and the shadowed parts represented the number which showed the transition at the boundaries in them. Then, it was clear that only the grain boundariy was not always as essential factor for the transition. From the figure(b), it was shown that the depth of the initiation crack was distributed with the peak value of 40-50 μm. Then, the validity of the early growth model of microcracks in Fig.5 were confirmed from these results.

Figure 7 shows some examples of the relations between the crack depth b and the number of cracks M. The depth of cracks observed at the cross section were divided with the division of 10 μm. In the figure, as the distribution of b may be expressed nearly as an exponential ditribution. Figure 8 shows the plots on Weibull probability paper with rearrangement of the results in Fig.7. From the figure, as these plotted points were approximated with two straight lines when b above 40-50 μm were in existence($N/N_f \geq 50\%$ in

the figure), it was found to be able to express with a composite Weibull distribution which was divided by the value of δ. Then, a probability density function(pdf) of the distribution f(b) is shown as follows,

$$\left.\begin{array}{ll} f_1(b) = \frac{m_1}{\alpha_1}(b-\gamma_1)^{m_1-1} \exp\{-\frac{(b-\gamma_1)^{m_1}}{\alpha_1}\}, & \gamma_1 \leq b < \delta \\ f_2(b) = \frac{m_2}{\alpha_2}(b-\gamma_2)^{m_2-1} \exp\{-\frac{(b-\gamma_2)^{m_2}}{\alpha_2}\}, & \delta \leq b \end{array}\right\} \quad \text{----------} (2)$$

where, m_1 and m_2 are shape parameters, α_1 and α_2 scale parameters, γ_1 and γ_2 location parameters and δ a separation parameter, respectively. Judging from Fig.8 and so on, it was assumed that both of γ_1 and γ_2 were eaqual to zero. Figures 9 and 10 show dependences of stress amplitude σ_a and ratio of cycles N/N_f on these parameters m, α and δ, respectively. Both m_1 and m_2 don't depend on them, and it is obtained as $m_1 \mp 0.5$ and $m_2 \mp 1.0$, respectively. Therefore, the cracks beyond the value of δ shows approximately the exponential distribution. The values of α_1 and α_2 don't show clear dependence on σ_a, but they increase with N/N_f. Next, the value of δ show the dependence on σ_a, such as decreasing tendency with σ_a. As the value of δ was about 50 μm, being about two grain sizes, it was assumed that δ was equivalent to the initiation crack depth in Fig.5.

From the results and the discussions, the initiation and the early growth behaviors of fatigue microcracks on smooth bar materials were quarified quantitatively.

REFERENCES

[1] M.Klesnil, et al., J.Iron and Steel Inst., 47(1965)203.
[2] P.J.E.Forsyth, The Physical Basis of Metal Fatigue, (1967)57, Blackie.
[3] H.Kobayashi and H.Nakazawa, Science of Machine, 25(1973)71.
[4] H.Kitagawa et al., ASTM STP 675, (1979)420.
[5] Y.Ochi et al., J.Soc.Mat.Sci.,Japan, 31(1982)559.
[6] S.Sasaki and Y.Ochi, Engg.Frac.Mech., 12(1979)531.
[7] H.Makabe, How to use Weibull propability paper,(1966)30,Jap.Stan.Assoc.

Table 1. Mechanical Properties.

Materials	Yield strength σ_Y(MPa)	Tensile strength σ_B(MPa)	Elongation (%)	Reduction of area (%)
0.07%c.st.	227.4	361.6	70.0	54.6
0.15%c.st.	233.2	407.7	41.0	54.4
0.16%c.st.	231.3	389.1	45.1	65.1

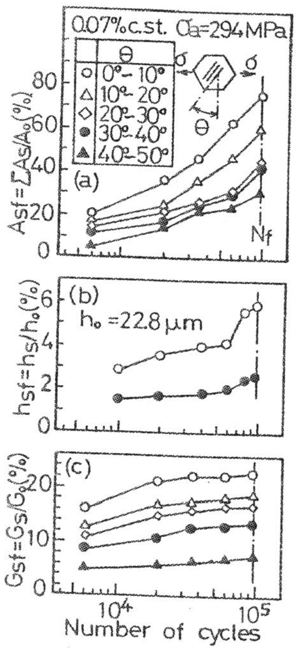

Fig.1 Variations of FSB's during fatigue process. (a)ratio of FSB's area, A_{sf}, (b)ratio of FSB's depth,h_{sf} and (c)ratio of number of slipped grains, G_{sf}.

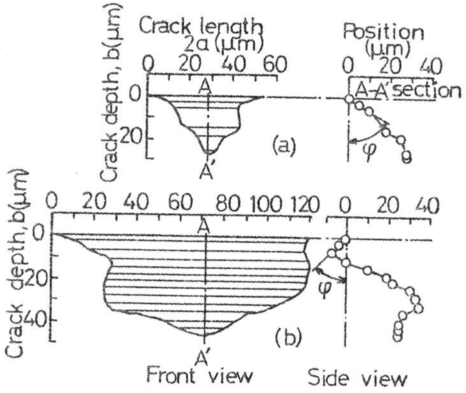

Fig.2 Crack shapes by surface polihing technique.

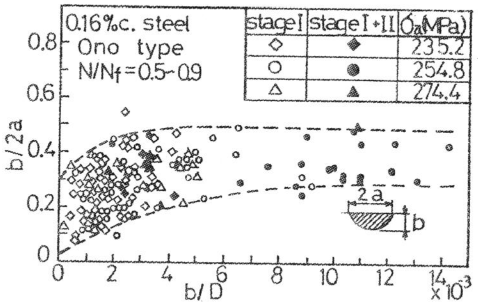

Fig.3 Crack aspect ratio(b/2a) by fractographic observation.

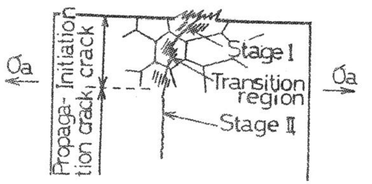

Fig.5 Schematic diagram of early growth stage of microcracks.

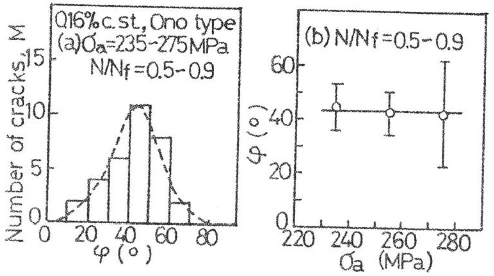

Fig.4 Initiation angle of microcracks (a) distribution of φ and (b) stress dependence of φ.

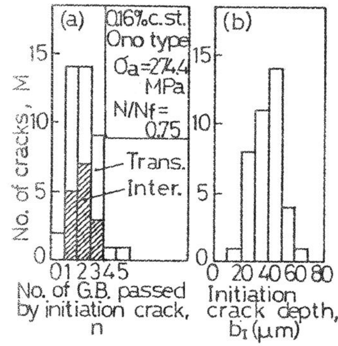

Fig.6 Number of grain boundaries passed by initiation cracks and the depth.

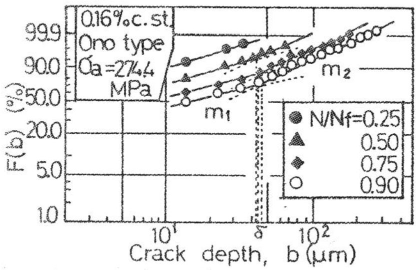

Fig.8 Weibull plots of crack depth.

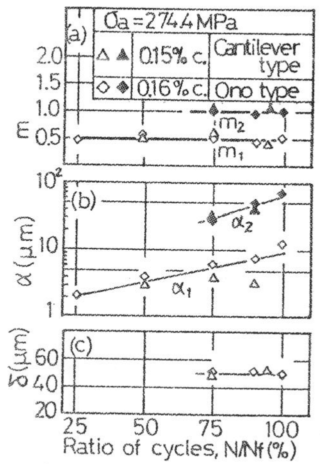

Fig.10 Dependence of Weibull parameters on ratio of cycles.

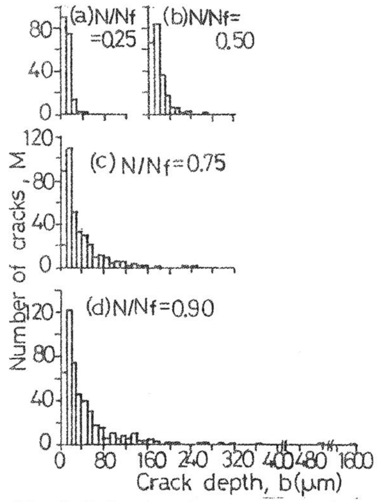

Fig.7 Relation between crack depth and number of cracks.

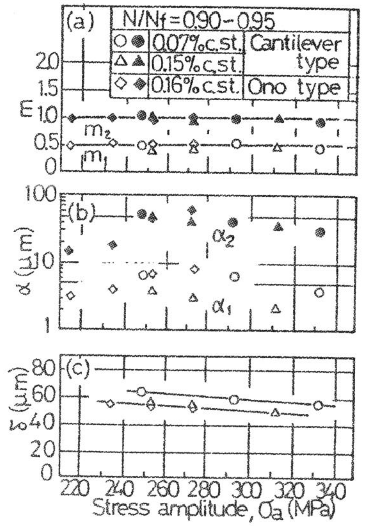

Fig.9 Dependence of Weibull parameters on stress amplitude,(a) shape parameter m, (b) scale parameter α ,(c)separation parameter δ .