Statistical Property in the Initiation and Propagation of Microcracks of a Heat-Treated 0.45% C Steel*

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The statistical property of the fatigue behavior was investigated for heat-treated 0.45% carbon steel plain specimens. The emphasis is to investigate separately the statistical properties of the initiation and propagation of microcracks through successive observations of the specimen surface through the plastic replica method. Results show that the Weibull distribution of the mixed type is well fitted to the microcrack initiation life distribution. On the other hand, the microcrack propagation life distribution and the crack length distribution are expressed as two- and three-parameter Weibull distributions, respectively.

Key Words: Fatigue, Statistical Treatment, Iron and Steel, Heat Treatment, Crack Initiation, Microcrack Propagation, Surface Defect, Weibull Distribution

1. Introduction

The statistical properties of fatigue damage must be investigated in order to evaluate the reliability of machines and structures. Many studies concerning the statistical treatment of fatigue data of plain specimens have been reported^{(1)~(8)}. The statistical properties of the initiation and propagation of small cracks must be studied separately to clarify the physical background of the statistical property of fatigue damage, because the fatigue life of a plain specimen is occupied mainly by the initiation and propagation lives of a small crack⁽⁹⁾.

Since heat-treated steels are very often used as the main materials for machines and structures which must perform under extreme service conditions, it is

meaningful to clarify the fatigue properties of heat-treated steels. Moreover, the effect of a defect on the fatigue strength increases with the increased hardness of the material. This seems to closely relate to the fact that fatigue data of high-strength materials usually have large scatter. Accordingly, the investigation of the statistical property of a heat-treated steel is crucial to the safe design of machines and structures.

In order to perform a detailed investigation of the initiation and propagation behavior of a microcrack, fatigue damage in the same region must be observed successively. However, such studies have been few and certain questions remain unanswered.

In the present research, rotating bending fatigue tests of heat-treated 0.45 % carbon steel plain specimens were carried out. The statistical property of fatigue damage was investigated through successive observations of the specimen surface, paying particular attention to the initiation and propagation behavior of microcracks.

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2. Material, Specimens and Experimental Procedures

The material used is a rolled round bar (about 19 mm in diameter) of 0.45 % carbon steel. The specimens were machined from the bars after heat treatment (normalizing for 30 minutes at 845°C, quenching for 30 minutes at 845°C and tempering for 60 minutes at 600°C). The chemical composition (Wt %) and mechanical properties after heat treatment are shown in Tables 1 and 2, respectively. Micrographs of the microstructure are shown in Fig. 1.

The shape and dimensions (in mm) of the specimen are shown in Fig. 2. The specimen surface was finished by longitudinal polishing with 600 grade silicon carbide paper. Before testing, the specimens were electropolished to remove about 3~5 μm from the surface layer in order to make the change of surface state easy to observe.

All the tests were carried out using a rotating bending fatigue machine of the uniform bending type with a capacity of 100 Nm operating at 3 600 rev/min.

The observations of fatigue damage on the speci-

Table 1 Chemical composition (Wt %)

C	Si	Mn	P	S	Cu	Ni	Cr
0.45	0.25	0.79	0.01	0.01	0.09	0.03	0.18

Table 2 Mechanical properties

MPa			%	Hv *
σ_{sl}	σ_{B}	σ_{T}	ψ	
750	833	1510	61.6	270

*Vickers hardness (Load: 9.8 N)

Fig. 1 Microstructure of the material

Fig. 2 Dimensions (in mm) of the specimen

men surface and the measurements of crack length and number of cracks were made via plastic replicas. That is, 12~18 pieces of a region whose area is about 1.7 mm² (=1.3 mm×1.3 mm) were set arbitrarily on the replicas gathered from the midsurface of a specimen, then photographs of these regions were taken at a magnification of 200. The initiation and propagation behavior of all the microcracks in the regions were analyzed based on the photographs. The observations for periodic measurements were also made with the optical microscope at a magnification of 400. The crack length, l , is the length along the circumferential direction on the specimen surface. The stress value means the nominal stress amplitude σ_a at the minimum cross section.

3. Experimental Results and Discussion

Figure 3 shows the S-N curve. In this study, the successive observations were made under four stress levels, $\sigma_a=550, 600, 650$ and 700 MPa ($1.2\sigma_w < \sigma_a < 1.6\sigma_w$, σ_w : fatigue limit) in order to clarify the statistical property of microcracks under stress, except near the fatigue limit. The statistical treatment was only applied to those specimens whose deviation from the mean Vickers hardness number is extremely small, because the statistical property of fatigue damage seems to be affected by scatter in the material property.

Figure 4 shows the scatter in the Vickers hardness of the specimens represented on normal probability paper. The distribution of the Vickers hardness of this material is represented approximately by the normal distribution in the same manner as for other materials⁽¹⁰⁾⁽¹¹⁾, and its mean value is about 270. Vickers hardness numbers of the specimens to which statistical treatment was applied are near this mean value ($H_v=267, 269, 270$ and 271). The statistical properties obtained are described in the following sections.

Fig. 3 S-N curve

3.1 Statistical property of the microcrack initiation

Figure 5 shows the relation between the relative number of cycles N/N_f and the crack density δ given by the mean value of the number of cracks in 1 mm^2 . The crack density increases with the increase in the relative number of cycles and stress amplitude.

The fatigue strength of high-strength materials is generally affected by surface defects. Figure 6 shows the change in surface states around a crack; Fig. 6 indicates that both the small defect and slip band must be considered as the starting site of microcracks.

Figure 7 shows the ratio of the number of cracks

Fig. 4 Vickers hardness distribution represented on normal probability paper

Fig. 5 Relation between the crack density and the relative number of cycles

initiated from defects to the total number of cracks. The ratio of cracks from defects increases with a decrease in stress level and decreases with an increase in N/N_f .

Many reports⁽³⁾⁻⁽⁸⁾ indicate that the distributions of fatigue life and crack length are expressed by the Weibull distribution⁽¹²⁾. Here, the three-parameter Weibull distribution function $F(x)$ is expressed by the following equation:

(a) case of a crack initiated from slip bands

(b) case of a crack initiated from defect

Fig. 6 Change in surface states around the crack

Fig. 7 Ratio of number of cracks initiated from defects to total number of cracks

$$F(x) = 1 - \exp\left\{-\left(\frac{x-\gamma}{\eta}\right)^m\right\} \quad (1)$$

where the three constants m , η and γ are the shape parameter, scale parameter and location parameter, respectively. In the following parts, the statistical property is examined based on the application of the Weibull distribution to each set of data.

Figure 8(a) shows the initiation life distribution of all the microcracks observed at $0.9N_f$. Each datum is on a curved line approximately. Here, taking account of the experimental result that the maximum crack length at the time of initiation is smaller than $25 \mu\text{m}$, the initiation life N_i is defined by the number of cycles when the crack length reaches $25 \mu\text{m}$. On the other hand, when the starting site of crack is divided into two sites, defect and slip band, the data in both cases are as shown in Fig. 8(b). The microcrack initiation life distribution in each case is approximated by a straight line. This means that the crack initiation life distribution, in which the starting site of crack is distinguished, is expressed as a two-parameter Weibull distribution. The straight lines in Fig. 8(b) are the distribution functions calculated based on the least squares method.

Figure 8(b) suggests that the distribution of N_i in Fig. 8(a) is represented by a Weibull distribution of mixed type:

$$F(N_i) = pF_D(N_i) + qF_S(N_i) \quad (2)$$

$$p + q = 1 \quad (3)$$

$$F_D(N_i) = 1 - \exp\left\{-\left(\frac{N_i}{\eta_D}\right)^{m_D}\right\} \quad (4)$$

Fig. 8 Microcrack initiation life distribution represented on Weibull probability paper

$$F_S(N_i) = 1 - \exp\left\{-\left(\frac{N_i}{\eta_S}\right)^{m_S}\right\} \quad (5)$$

where $F_D(N_i)$ and $F_S(N_i)$ are two-parameter Weibull distribution functions in which the starting sites of cracks are the defect and slip band, respectively. The p and q are the probabilities of occurrence. A curved full line in Fig. 8(a) shows the distribution function analyzed by Eq. (2); it is well fitted to the experimental results. Table 3 shows the relation between the probability of occurrence and the Weibull parameters in $F_D(N_i)$ and $F_S(N_i)$. The value of p decreases with an increase in the stress level.

3.2 Statistical property of the microcrack propagation

Figure 9 shows the propagation curves of cracks larger than $200 \mu\text{m}$, the lengths of which are measured at the final measurement just before fracture (although 23 cracks were larger than $200 \mu\text{m}$, the propagation curves of 13 representative cracks are shown in Fig. 9). The $\bullet$ - and $\circ$ - marks correspond to the cracks initiated from the defect and slip band, respectively. No significant difference in the propagation behavior of cracks with different starting sites is

Table 3 Values of Weibull parameter in $F_D(N_i)$, $F_S(N_i)$ and probability of occurrence

MPa	$F_D(N_i)$			$F_S(N_i)$		
	m_D	$\eta_D(\times 10^4)$	p	m_S	$\eta_S(\times 10^4)$	q
550	4.5	6.2	0.24	7.2	7.3	0.76
600	6.6	2.5	0.18	12.5	3.1	0.82
650	5.3	0.9	0.12	13.2	1.1	0.88
700	8.1	0.5	0.09	10.7	0.6	0.91

Fig. 9 Propagation curves of cracks whose lengths are larger than $200 \mu\text{m}$

observed.

The scatter in the crack propagation life seems to be controlled mainly by the behavior of cracks whose lengths are relatively small. Therefore, the statistical property of crack propagation is investigated, paying particular attention to the behavior of cracks smaller than 100 μm .

Figure 10 shows the crack propagation life distribution plotted on Weibull probability paper. N_{100} is the life in which a crack propagates from its initial size ($=25\text{ }\mu\text{m}$) up to 100 μm . The experimental result under each stress level is approximated by a straight line, namely the distribution of N_{100} is represented by the two-parameter Weibull distribution. The $m-\sigma_a$ and $\eta-\sigma_a$ relations are given in Figs. 11 and 12, respectively.

3.3 Statistical property of the crack length distribution

Figure 13 shows the crack length distribution data at various stages of fatigue life represented on

Fig. 10 Weibull distribution of N_{100} : the life in which a crack propagates from its initial size up to 100 μm

Fig. 11 Relation between the shape parameter and the stress level

Weibull probability paper. The curved lines in this figure show those distribution functions whose three Weibull parameters are calculated based on the correlation factor method, that is the Weibull parameters at each N/N_f are determined so that the correlation coefficient for the linear regression becomes the maximum value. The experimental results are in good agreement with the distribution function. The distribution of crack length is represented by the three-parameter Weibull distribution, as with other materials⁽³⁾⁽⁵⁾.

Figure 14 shows the relation between the shape parameter m of the crack length distribution and the relative number of cycles at each stress level. When the stress range is constant, the value of m is nearly constant independent of N/N_f . Although there is a tendency for the value of m to increase with an increase in stress level, its value in the range of 600

Fig. 12 Relation between the scale parameter and the stress level

Fig. 13 Crack length distributions at various stages of the fatigue life

MPa $\leq \sigma_a \leq 700$ MPa is nearly equal to unity, $m=0.9 \sim 1.1$. However, the value of m in $\sigma_a=550$ MPa is smaller than unity, $m \approx 0.6$.

Figure 15 shows the relation between the scale parameter η and N/N_f at each stress level. The dependency of the $\eta-N/N_f$ relation on stress in the range $600 \text{ MPa} \leq \sigma_a \leq 700$ MPa cannot be clearly observed, but this relation can be approximated by a straight line. Although the $\eta-N/N_f$ relation in $\sigma_a=550$ MPa can also be represented by a straight line, its relation is different from that in $\sigma_a \geq 600$ MPa.

Figure 16 shows the distribution of crack lengths at various stages of fatigue life. The white and black parts in the histograms correspond to the number of

cracks initiated from the slip band and defects, respectively. Figure 16(a) shows the case for $\sigma_a=650$ MPa and (b) is 550 MPa. For both the stress levels, many cracks initiate from the defect in the early stages of cycling. When we compare Figs. 16(a) and 16(b), we can recognize that the transitions of crack length distributions are different from each other. For case (a), both the crack length and the number of cracks

Fig. 14 Dependency of shape parameter on the relative number of cycles under several stress amplitudes

Fig. 15 Dependency of scale parameter on the relative number of cycles under several stress amplitudes

Fig. 16 Transition of crack length distribution

increase successively with increasing N/N_f (it is also confirmed that this tendency nearly holds at stress levels of 600 and 700 MPa). For case (b), the increase in crack lengths is remarkably large, whereas the increase in the number of cracks is not so large. That is, the crack length distribution under 550 MPa is strongly affected by the behavior of cracks initiated from defects at the early stages of cycling, and this fact closely relates to the value of m smaller than unity.

When we analyze the life distribution by using Weibull distribution, the type of life distribution is usually divided into the following three types in accordance with the magnitude of m : (i) initial failure for $m < 1$, (ii) chance failure for $m = 1$ and (iii) wearout failure for $m > 1$. In the present experiment, the values of m in $\sigma_a = 600 \sim 700$ MPa are about unity and correspond to the chance failure, whereas m in $\sigma_a = 550$ MPa is about 0.6 (< 1), which corresponds to the initial failure. As stated for Fig. 16(b), $m \cong 0.6$ results from the governing propagation of cracks initiated in the early stages of cycling. The other result obtained from Fig. 16 is as follows: the number of cracks from defects tends to be saturated with an increase in the number of cyclings, however the number of cracks from the slip band increases with cycling.

4. Conclusions

Rotating bending fatigue tests of heat-treated 0.45 % carbon steel plain specimens were carried out and successive observations on the specimen surface were made by the plastic replica method. Statistical treatment was applied to the data in order to clarify the statistical property of the initiation and propagation of microcracks under the constant stress amplitude in the range $1.2\sigma_w < \sigma_a < 1.6\sigma_w$, σ_w : fatigue limit. The results are summarized as follows.

(1) The starting site of microcrack in this material can be divided into the following two sites: (i) small surface defect and (ii) slip band.

(2) The initiation life distributions of microcracks from the defect and slip band are represented by the two-parameter Weibull distribution functions $F_D(N_i)$ and $F_S(N_i)$, respectively.

$$F_D(N_i) = 1 - \exp\left\{-\left(\frac{N_i}{\eta_D}\right)^{m_D}\right\}$$

$$F_S(N_i) = 1 - \exp\left\{-\left(\frac{N_i}{\eta_S}\right)^{m_S}\right\}$$

On the other hand, when the initiation life is not distinguishable by the difference in the starting site of a crack, the distribution of the microcrack initiation life can be represented by the Weibull distribution of mixed type:

$$F(N_i) = pF_D(N_i) + qF_S(N_i)$$

where, the p and q are the probabilities of occurrence. The value of p decreases with an increase in the stress range.

(3) The distribution of microcrack propagation life (the life in which a crack propagates from an initial size, 25 μm in this material, up to 100 μm) is represented by the two-parameter Weibull distribution.

(4) The distribution of crack length is represented by the three-parameter Weibull distribution. The shape parameter m and scale parameter η have the following characteristics according to the magnitude of stress:

(i) In the case when the stress is relatively large ($\sigma_a > 1.3\sigma_w$): the value of m is nearly equal to unity ($m = 0.9 \sim 1.1$), though only slight dependency of m on stress is observed. The value of η can be estimated approximately in terms of a function of the relative number of cycles N/N_f only.

(ii) In the case when the stress is relatively small ($\sigma_a \cong 1.2\sigma_w$): the value of m is smaller than unity ($m \cong 0.6$), and the $\eta - N/N_f$ relation is different from that under high stress levels.

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