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On the Crack Propagation by Cyclic Stresses

below the Fatigue Limit in Specimens with a Pinhole*

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The fatigue crack propagation by the cyclic stress below the fatigue limit in specimens with a pinhole is investigated after the crack initiation by the over-stress. The test results show that the critical condition for the start of crack propagation in a cracked specimen is indicated by $\sigma_1^3 l = 1.6 \times 10^5 \text{ (kg/mm}^2\text{)}^3 \text{mm}$ as the relation between the crack length and the applied stress value. In some cases, a fatigue crack propagates under a cyclic stress below the fatigue limit and afterwards stops to propagate. In this case, the crack length l_2 is greater in the case when the crack initiating stress is higher. When the cyclic stress over the fatigue limit is applied after a crack propagation has been stopped by the under-stress, the crack propagating rate is reduced in the first period of crack propagation.

1. Introduction

The greater part of service loads is represented by stress amplitudes below the fatigue limit, and the effects of those stress amplitudes on the fatigue life have been made clear as the result of the program fatigue tests carried out by the authors and others. The experimental results that the fatigue lives are shorter than those estimated by Miner's law are also reported^{(1) (3)}. As to the cause for decreasing the fatigue lives, an observation of plastic strains and the crack propagating behavior under stress amplitudes below the fatigue limit is reported^{(4) (5)}.

On the other hand, it is reported also that stress amplitudes below the fatigue limit give negativ damage on the material and the fatigue strength is merely elevated. In order to make clear the effect of stress amplitudes below the fatigue limit on fatigue lives, the crack propagation, which has been initiated by a stress amplitude above the fatigue limit, by a stress amplitude below the fatigue limit, and also after the crack propagated by stress amplitudes below the fatigue limit, the crack propagation by a stress amplitude above the fatigue limit are investigated on specimens with a pinhole. These specimens are used on account of easiness of the observation of a surface crack.

As the result of these experiments, the condition to start the crack propagation by the stress amplitude σ_2 below the fatigue limit, after the crack length l reaches l_1

by the repetition of the stress amplitude σ_1 above the fatigue limit, has been found to be able to be expressed by the following formula in the same way as the perforated cylindrical specimens⁽³⁾, and this relation holds good independently of the value of $\sigma_2^3 l_2 = \text{const.}$

It has also been made clear that after the stress amplitude below the fatigue limit is repeated, the crack propagating rate by stress amplitudes above the fatigue limit is retarded. These results will be discussed in this paper.

2. Experimental procedure

Fatigue tests under constant stress amplitudes are carried out on specimens with a pinhole, and S-N diagrams and crack propagating curves are obtained. Crack propagation by the repetition of each stress amplitude is measured by a two steps three-fold program fatigue test in which are applied the primary stress σ_1 above the fatigue limit, the secondary stress σ_2 below the fatigue limit and the tertiary stress σ_3 , equal to σ_1 , above the fatigue limit as shown Fig. 1. In the figure, n_1' and n_2' show the number of cycles of the tertiary stress, $\sigma_3 = \sigma_1$ and the effect of the repetition of σ_2 on the crack propagation by σ_1 is investigated.

Fig. 1 Two steps three-fold stress pattern

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2.1. Test specimens

The material used in this experiment is carbon steel S35C. The chemical compositions and mechanical properties of the material are shown in Table I and Table II. The dimensions of the test specimens are shown in Fig. 2. After machining hot rolled bars to the dimensions of the specimen, the surface is polished with emery paper of #06, and then the specimens are drilled to open a hole 0.2 mm in diameter and 0.2 mm in depth, as shown in Fig. 2a, at the center of parallel part of 10 mm diametral, and finally the surface is polished again with emery paper of #06 in the longitudinal direction. Stress concentration factor is about 2.85 when the hole is bored into the specimen. Fig. 2b shows the dimensions of plain specimens of sand glass type in which the radius of curvature is 95 mm.

2.2. Testing apparatus

An Ono type rotating uniform bending fatigue testing machine (2800 rpm) is used.

2.3. Observation of cracks

In order to measure the fatigue crack length on the surface of specimens, a replica of a crack is taken by attaching an acetyl cellulose film using methyl acetate as solvent as shown in Fig. 3. The crack length in this experiment is defined as the distance between two crack tips propagated from both ends of a hole at the center of specimens, and is denoted as l . Accordingly, the crack length includes the diameter of the hole, and is read by a tool maker's

Table 1 Mechanical properties

σ_{so} kg/mm ²	σ_{su} kg/mm ²	σ_B kg/mm ²	δ %	φ %
41.7	33.5	52.1	28.3	62.4

Table 2 Chemical compositions (%)

C	Si	Mn	P	S	Cu	Ni	Cr
0.25	0.22	0.54	0.01	0.02	0.05	0.01	0.03

Fig. 2 Shape and dimensions of specimens

microscope.

3. Experimental results and discussion

In the first place, conventional fatigue tests under constant stress amplitudes are carried out to get S-N curves, and crack propagating curves are obtained at constant stress amplitudes of 30, 25 and 19 kg/mm². Then, two steps and three-fold fatigue tests, as shown in Fig. 1, including stress amplitudes above and below the fatigue limit, are carried out, and the crack propagation by stress amplitude σ_2 below the fatigue limit, and also the crack propagation by tertiary stress σ_3 above the fatigue limit are investigated. The stresses in this paper are all expressed as nominal ones.

3.1 Conventional fatigue test

The conventional S-N curves under constant stress amplitudes are shown in Fig. 4, in which nominal stress amplitudes are taken in ordinate and the number of cycles to failure in abscissa, both on logarithmic scale. In this figure, symbol $\circ$ denotes the experimental points for plain specimens, the fatigue limit for this specimens being about 24.5 kg/mm², and symbol $\bullet$ does the experimental points on specimens with a pinhole, the fatigue limit

Fig. 3 Crack measurement

Fig. 4 S-N diagram

for these specimens being about 19.5 kg/mm^2 . The fatigue notch factor β is about 1.3.

Fig. 5 shows the crack propagating curves under constant stress amplitude fatigue tests on specimens with a pinhole. In the figure, crack length is given in ordinate in logarithmic scale, and the number of stress cycles on abscissa on uniform scale. The symbol X in this figure indicates only the number of stress cycles to failure and does not mean the crack length when a fracture occurred.

Fig. 5a and Fig. 5b show the crack propagating curves when the stress amplitudes are 30 kg/mm^2 and 25 kg/mm^2 respectively. Three specimens are tested in each experiment. If the crack propagating curves are assumed to be expressed by straight lines, in these figures, the crack propagating rate is expressed by Eq. (1).

$$\frac{dl}{dN} = C_1 \quad (1)$$

Eq. (1) means that the crack propagating rate increases in proportion to the crack length, and this tendency coincides with the crack propagation in perforated cylindrical specimens reported on previously by the authors.

Fig. 5c shows a crack propagating curve of a crack initiated and propagated by the repetition of the stress amplitude of 19 kg/mm^2 , but the specimen does not fracture till the number of stress cycles amounting to 1.023×10^7 , and the crack

Fig. 5a Crack propagating curves under constant stress ($\sigma = 30 \text{ kg/mm}^2$)

Fig. 5b Crack propagating curves under constant stress ($\sigma = 25 \text{ kg/mm}^2$)

propagation is stopped. The non-propagating crack length is about 0.4 mm .

3.2 The crack propagation by the repetition of the stress amplitude below the fatigue limit

Crack propagation, initiated by the repetition of primary stresses such as 30 , 25 and 21 kg/mm^2 which are above the fatigue limit, is investigated under the secondary stress below the fatigue limit σ_2 such as $6 \sim 19 \text{ kg/mm}^2$.

Fig. 6 shows the crack propagating behavior under the repetition of the secondary stress σ_2 after the crack length attains l_1 by the repetition of the primary stress σ_1 of 30 kg/mm^2 which is above the fatigue limit. In this figure, the primary crack length l_1 is represented in ordinate and the secondary stress σ_2 in abscissa, both on logarithmic scale. In the figure, the symbol $\bullet$ means that the crack does not propagate by the repetition of the stress σ_2 , the symbol $\circ$ means that the crack propagates by the stress σ_2 , but the crack propagating rate becomes slow with an increase in the number of stress cycles and the crack propagation is stopped finally;

Fig. 5c Crack propagating curve under constant stress ($\sigma = 19 \text{ kg/mm}^2$)

Fig. 6 Condition of the crack propagation under secondary stress ($\sigma_1 = 30 \text{ kg/mm}^2$)

and the symbol ● does that the crack continues propagating to failure by the stress σ_2 . The straight line in these figures shows the crack propagating condition $\sigma_2^m l_1 = \text{constant}$, proposed by N. E. Frost. When m is taken equal to 3 the straight lines coincide well with the experimental results as shown in Fig. 6 to Fig. 8. From these results, it is clear that cracks do not propagate under the combination of the stress amplitude σ_2 and the crack length l_1 in the region below the straight line; and under the combination of σ_2 and l_1 in the region above the straight line the crack propagates and then stops, or continues propagating to failure.

Fig. 7 and Fig. 8 show crack propagation by the repetition of σ_2 after the crack length attains l_1 mm by the primary stress σ_1 , such as 25 and 21 kg/mm² respectively in the same manner as Fig. 6. In these figures, the meanings of the symbols are similar to those in Fig. 6. According to the experimental results, the crack propagating condition is expressed by the equation $\sigma_2^m l_1 = \text{constant}$, proposed by N. E. Frost, in the same manner as Fig. 6. In Fig. 6 to Fig. 8, the straight lines are expressed by the following equation.

$$\sigma_2^3 l_1 = 1.6 \times 10^3 \quad (\text{kg/mm}^2)^3 \text{mm}$$

From these results, it is clear that there is little effect of the magnitude of the primary stress on the crack propagating behavior by secondary stresses. The value of the right side of above equation is about three times that shown by N. E. Frost in the case of mild steel. The reason is in the differences in materials, shapes of specimens and loading conditions.

When the primary crack length l_1 is shorter than the nonpropagating crack length

as shown Fig. 5c, the crack propagates and then stops as shown in Fig. 6 and Fig. 7; for instance, when l_1 is 0.3 mm and σ_2 is 19 kg/mm² the crack continues propagating till fracture occur, but when l_1 is 0.3 mm and σ_2 is 17 kg/mm² the crack propagates and then stops. It seems that the crack tip condition in the case of

When the primary crack length l_1 is shorter than the non-propagating crack length as shown Fig. 5c, the crack propagates and then stops as shown in Fig. 6 and Fig. 7; for instance, when l_1 is 0.3 mm and σ_2 is 19 kg/mm² the crack continues propagating till fracture occur, but when l_1 is 0.3 mm and σ_2 is 17 kg/mm² the crack propagates and then stops. It seems that the crack tip condition in the case of non-propagating crack is different from that in the case of propagating crack by a stress above the fatigue limit, though the primary crack length l_1 is the same.

The reason why the crack propagation by the secondary stress is not affected by the magnitude of the primary stress as shown in Fig. 6 to Fig. 8, is considered as follows, without doing the experimental verification. Whether a crack propagates or not is determined by the state of the crack tip. As to the state of the crack tip, the shape of the crack tip and the change of mechanical properties at the crack tip due to stress repetitions are to be considered. The shape of the crack tip is assumed to be nearly constant irrespective of the magnitude of the stress which propagates the crack, when the primary stress σ_1 above the fatigue limit is such as 30, 25 and 21 kg/mm². As to the change of mechanical properties at the crack tip, growth of residual stresses and variation

Fig. 7 Condition of the crack propagation under secondary stress ($\sigma_1 = 25 \text{ kg/mm}^2$)

Fig. 8 Condition of the crack propagation under secondary stress ($\sigma_1 = 21 \text{ kg/mm}^2$)

of hardness are presumed. As residual stresses are said not to affect the crack initiation(7), the magnitude of cyclic stress σ_1 is assumed not to affect the crack propagating condition.

The crack propagating curves by σ_2 in the specimen with a crack of length l_1 propagated by σ_1 are shown in Fig. 9 to Fig. 13 and Table III. In these figures, the secondary crack length l_2 is represented in ordinate and the number of cycles n_2 of σ_2 in abscissa. Here, l_2 is the length of a crack propagated by only the repetition of σ_2 , hence, $l_2 = l - l_1$. l_2^* means the crack length propagated by the secondary cyclic stress σ_2 till the crack propagation stops.

Fig. 9 shows the crack propagating curves when the secondary stress σ_2 of 15 kg/mm² is applied, after the crack length reaches about 1.6 mm by the repetition of primary stress σ_1 such as 30, 25 and 21 kg/mm². In this figure, mark O denotes the experimental points when σ_1 is 30 kg/mm² and marks ● and ● do the experimental points when σ_1 is 25 and 21 kg/mm² respectively. In the following figures,

Table 3 Crack propagation and it's stop by secondary stress

σ_1 kg/mm ²	l_1 mm	σ_2 kg/mm ²	n_2 c.	l_2^* mm
30	1.645	15	7.04×10^5	1.175
25	1.611	"	7.895×10^5	0.193
21	1.824	"	1.704×10^6	0.155
30	3.080	12	3.803×10^6	0.557
25	2.983	"	8.181×10^6	0.199
21	2.953	"	2.591×10^6	0.067
30	4.015	12	4.015×10^6	0.737
25	4.057	"	3.962×10^6	0.195
21	4.006	"	1.642×10^6	0.099
30	5.002	11	2.903×10^6	0.928
25	4.984	"	4.234×10^6	0.315
21	5.162	"	2.511×10^6	0.139
30	7.094	11	7.08×10^6	2.025
25	7.005	"	3.667×10^6	0.597
21	7.010	"	2.774×10^6	0.525

Fig. 9 Crack propagation by secondary stress ($l_1 = 1.6$ mm)

marks O, ● and ● denote the same stress condition as in Fig. 9. When σ_1 is 30 kg/mm², in Fig. 9, a crack continues propagating without stop by the repetition of σ_2 . On the other hand, when σ_1 is 25 and 21 kg/mm² respectively, a crack propagates rapidly in the early stage and afterwards stops propagation.

Fig. 10 shows the crack propagating curves when the secondary stress σ_2 of 12 kg/mm² is applied, after the crack length l_1 reaches about 3 mm by the repetition of primary stress σ_1 such as 30, 25 and 21 kg/mm². Fig. 11 to Fig. 13 show the similar crack propagating curves to Fig. 10 for different values of σ_2 and l_1 .

Fig. 10 Crack propagation by secondary stress ($l_1 = 3$ mm)

Fig. 11 Crack propagation by secondary stress ($l_1 = 4$ mm)

Some examples, in which a crack propagates to failure and a crack propagates rapidly in the early stage but afterwards propagates slowly and at last the crack propagation stops, by the repetition of the secondary stress, are shown in Fig. 9 to Fig. 13. From the experimental results, it is clear that a crack with length l_1 propagated by only the secondary stress till the crack propagation stops, becomes longer as

Fig. 12 Crack propagation by secondary stress ($l_1 = 5$ mm)

the primary stress is higher. This behavior coincides with the experimental results carried out already for perforated cylindrical specimens by authors.

The main reason for the fact that the crack length l_2 , propagated by the repetition of the secondary stress σ_2 , is greatly varied by the value of the primary stress σ_1 , though the crack length l_1 is constant at that time, is considered because

Fig. 13 Crack propagation by secondary stress ($l_1 = 7$ mm)

Table 4 The effects of the repetition of σ_2 on the crack propagation by σ_1

σ_2 kg/mm ²	$l_1 + l_2^*$ mm	σ_1 kg/mm ²	n_1'' c	n_1''' c	l_{n1}' mm	l_{n1}'' mm	l_{n1}'/n_1' mm/c	l_{n1}''/n_1''' mm/c
17	0.609	30	2×10^3	2×10^3	0.034	0.042	1.7×10^{-5}	2.1×10^{-5}
15	0.208	"	2×10^3	2×10^3	0.053	0.055	2.65×10^{-5}	2.75×10^{-5}
12	0.970	"	2×10^3	2×10^3	0.073	0.077	3.65×10^{-5}	3.85×10^{-5}
9	2.299	"	2×10^3	2×10^3	0.180	0.276	0.90×10^{-4}	1.38×10^{-4}
8	2.823	"	2×10^3	2×10^3	0.254	0.410	1.27×10^{-4}	2.05×10^{-4}
7	3.503	"	2×10^3	2×10^3	0.398	0.597	1.99×10^{-4}	2.99×10^{-4}
12	3.637	"	10^3	10^3	0.111	0.131	1.11×10^{-4}	1.31×10^{-4}
12	3.648	"	10^3	10^3	0.132	0.164	1.32×10^{-4}	1.64×10^{-4}
★17	4.490	"	1.5×10^3	1.5×10^3	0.208	0.304	1.39×10^{-4}	1.20×10^{-4}
7	4.574	"	2×10^3	2×10^3	0.609	0.863	3.05×10^{-4}	4.32×10^{-4}
11	5.930	"	1.5×10^3	1.5×10^3	0.290	0.396	1.93×10^{-4}	2.64×10^{-4}
6	6.745	"	10^3	10^3	0.238	0.262	2.38×10^{-4}	2.62×10^{-4}
6	7.273	"	2×10^3	2×10^3	0.515	0.704	2.58×10^{-4}	3.52×10^{-4}
15	0.573	25	10^4	10^4	0.023	0.068	2.3×10^{-6}	6.8×10^{-6}
13	0.741	"	10^4	10^4	0.019	0.055	1.9×10^{-6}	5.5×10^{-6}
12	0.946	"	10^4	10^4	0.043	0.087	4.3×10^{-6}	8.7×10^{-6}
11	1.160	"	2×10^4	2×10^4	0.394	0.711	3.94×10^{-5}	7.11×10^{-5}
12	1.195	"	10^4	10^4	0.053	0.073	5.3×10^{-6}	7.3×10^{-6}
15	1.805	"	10^4	10^4	0.121	0.122	1.21×10^{-5}	1.22×10^{-5}
9	2.087	"	10^4	10^4	0.149	0.163	1.49×10^{-5}	1.63×10^{-5}
12	3.182	"	10^4	10^4	0.214	0.304	2.14×10^{-5}	3.04×10^{-5}
12	4.252	"	10^4	10^4	0.303	0.429	3.03×10^{-5}	4.29×10^{-5}
★19	4.637	"	2×10^3	2×10^3	0.125	0.110	6.25×10^{-5}	5.50×10^{-5}
7	5.131	"	4×10^3	4×10^3	0.225	0.252	5.62×10^{-5}	6.30×10^{-5}
11	5.286	"	10^4	2×10^4	0.425	1.294	4.25×10^{-5}	6.47×10^{-5}
7	5.597	"	5×10^3	5×10^3	0.335	0.343	6.70×10^{-5}	6.86×10^{-5}
7	6.292	"	10^4	10^4	0.712	0.846	7.12×10^{-5}	8.46×10^{-5}
9	7.045	"	2×10^3	2×10^3	0.876	1.738	4.38×10^{-4}	8.69×10^{-4}
12	0.737	21	4.06×10^4	4.4×10^4	0.032	0.071	0.788×10^{-6}	1.62×10^{-6}
12	1.073	"	1.4×10^3	10^3	0.144	0.407	1.03×10^{-6}	4.07×10^{-6}
15	2.073	"	2×10^4	2×10^4	0.048	0.136	2.4×10^{-6}	6.8×10^{-6}
9	2.246	"	3.3×10^4	4.2×10^4	0.146	0.277	4.42×10^{-6}	6.60×10^{-6}
12	3.020	"	4×10^4	4×10^4	0.336	0.518	0.84×10^{-5}	1.30×10^{-5}
8	3.164	"	1.1×10^4	1.1×10^4	0.079	0.128	7.18×10^{-6}	1.16×10^{-5}
8	3.392	"	3×10^4	3×10^4	0.349	0.357	1.16×10^{-5}	1.19×10^{-5}
12	4.105	"	3×10^4	3.5×10^4	0.493	0.653	1.64×10^{-5}	1.86×10^{-5}
7	5.234	"	5×10^3	2×10^3	0.046	0.057	0.92×10^{-5}	2.85×10^{-5}
11	5.442	"	10^4	2×10^4	0.122	0.590	1.22×10^{-5}	2.95×10^{-5}
6	7.111	"	10^4	10^4	0.234	0.547	2.34×10^{-5}	5.47×10^{-5}

the size of damaged zone at the crack tip depends upon the value of the primary stress σ_1 . As the size of the damaged zone is different by the value of σ_1 , the crack propagating behavior by the repetition of the secondary stress σ_2 is considered to be dependent upon the size of damaged zone ahead of the crack tip and the value of the secondary stress σ_2 . In the present experiment, in which σ_2 takes a constant value, the crack length l_2^* is considered to be varied by the size of the damaged zone due to σ_1 . But as the size and the grade of the damaged zone are not known, quantitative analysis is impossible.

3.3 The effect of the repetition of stress amplitudes below the fatigue limit on the crack propagating rate by the stress amplitude above the fatigue limit repeated afterwards

Two steps three-fold program fatigue tests are carried out as shown in Fig. 1, namely, the crack propagating rate is investigated, when σ_1 is again repeated, after the crack propagation by the repetition of σ_2 is observed. σ_1 is repeated for the number of n_1' and n_1'' cycles and the increments of the crack length l_{n1}' and l_{n1}'' propagated by the repetition of σ_1 are measured and then l_{n1}'/n_1' and l_{n1}''/n_1'' are calculated as shown in Table IV. In this table, the mark $\star$ at the top of the row shows the case in which the crack continues propagating without stop by the repetition of σ_2 . Other cases having no mark are ones in which the crack does not propagate or the crack propagates but stops afterwards.

According to the experimental results except in the case of mark $\star$, the crack propagating rate l_{n1}'/n_1' is smaller than l_{n1}''/n_1'' , and it is clear that after σ_2 is repeated the crack propagating rate by σ_1 is retarded when the crack propagation by the repetition of σ_2 is afterwards stopped, including the case of no propagation. When the crack is propagated by the repetition of σ_2 as shown by the mark $\star$, it is clear that there is no retarding effect on the crack propagating rate for the stress repetition afterwards. This experimental result shows that there is a strengthening effect at the crack tip, in which the crack propagating rate by the stress amplitude repeated afterwards is retarded when the crack propagation is stopped, unlike the crack tip in which the crack is propagated without stop by the cyclic stress. The strengthening effect is considered due to the radius of curvature at the propagating crack tip as shown by Okubo et al. (8)(9), and that the material strength being increased by the repetition of stress amplitude below the fatigue limit. The experimental fact that the crack is propagated by the repetition of the secondary stress though the primary crack is shorter than non-propagating crack as shown in Fig. 6 and Fig. 7, is also understandable from the present discussion.

As mentioned above, the effects of stress amplitudes below the fatigue limit

on the fatigue lives are considered as follows; one is that the crack propagates by the repetition of the stress amplitude below the fatigue limit as shown in Fig. 9 to Fig. 13 and another is that there is a retarding effect on the crack propagating rate at early stage of stress cycles repeated afterwards. These facts affect the fatigue lives positively and negatively. It seems that the fact that the repetition of the stress amplitude below the fatigue limit works negatively and positively on the fatigue lives, is one of the reasons that the experimental results of fatigue tests including the stress amplitudes below the fatigue limit have been complicated.

As cases in which only a stress amplitude below the fatigue limit acts upon mechanical structures for long period are rare, it is considered that the positive effect of stress amplitudes below the fatigue limit cannot be expected. Therefore, the number of cycles of the stress amplitude below the fatigue limit in the program fatigue tests should be set lower than the number of cycles in which the crack propagating rate by σ_2 is rapidly as shown in Fig. 9 to Fig. 13.

4. Conclusions

Crack propagation by the repetition of a stress amplitude below the fatigue limit in specimens having a fatigue crack, initiated by the repetition of a stress amplitude above the fatigue limit, is investigated on specimens with a pinhole of carbon steel S25C, and the following results are obtained.

(1) The crack propagating rate of specimens with a pinhole under constant stress fatigue tests is expressed by the following equation:

$$dl/dN = C_1.$$

(2) The stress value which is able to make successively the crack propagate, initiated by the stress amplitude above the fatigue limit, is expressed by the following relation which is independent of the magnitude of stress amplitude above the fatigue limit:

$$\sigma_2^3 l_1 = 1.6 \times 10^3 \quad (\text{kg/mm}^2)^3 \text{mm}$$

(3) Whether a crack initiated by the repetition of primary stress amplitude above the fatigue limit propagates successively or stops propagation afterwards by the repetition of the secondary stress is decided by the magnitudes of the primary stress amplitude above the fatigue limit and the secondary stress amplitude repeated afterwards.

(4) The crack length l_2^* is influenced by the magnitude of the primary stress and when the primary stress is larger, the crack length l_2^* is greater.

(5) When the crack has stopped its propagation (including the case that the crack does not propagate) by the repetition of the stress amplitude below the fatigue limit, the crack propagating rate by the repetition of the stress amplitude above the fatigue limit applied afterwards, is

retarded in the early stage, and when the crack is successively propagating, there is not such a retarding effect.

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