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Influences of Stress Cycle Frequency on Propagation of Corrosion Fatigue Cracks*

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Corrosion fatigue test of a mild steel in salt water has been carried out at various cycle frequencies ranging from 1400 c/min to 0.28 c/min to study corrosion fatigue mechanism. The following results have been obtained from the measurement of crack growth rate and the microscopic observation on the cross section and on the fractured surface of specimens.

At the cycle frequencies from 1400 c/min to 100 c/min, the decreases of the wedge action due to the hydrodynamic pressure of corrosion products are predominant for the increase of crack rate, and the crack rate increases at lower cycle frequencies with a decrease of the wedge effect. At the frequencies from 100 c/min to several cycles per minute, the wedge effect mentioned above becomes negligibly small, and the growth of crack width due to the corrosion of crack walls increases the crack rate at lower frequencies. At the cycle frequencies lower than several cycles per minute, the dissolution of crack tips increases the crack rate. However, at extremely lower frequencies a decrease of crack rate is sometimes caused by a remarkable branching of crack tips.

1. Introduction

In corrosive environment fatigue cracks are generated in the early stage of lives and the most part of fatigue lives is occupied by the period of crack propagation, so that it is very important to observe the crack growth behavior in corrosion fatigue. Crack propagation is affected by corrosion intensity as well as by stress cycle frequency, and a strong correlation between them is suspected. Though corrosion fatigue lives vary in general proportionately with the logarithmic value of stress cycle frequency, these frequency effects diminish in low frequency range⁽¹⁾ and at extremely low frequencies complicated variations are observed depending upon materials, where the influence of strain wave form becomes more important than that of stress cycle frequency^{(2)~(4)}. The influence of cycle frequency varies depending upon the activity, the shape and the dimension of crack tips as well as upon the wedge action due to corrosion products in cracks⁽⁵⁾. However, detailed mechanism of the frequency effect remains unexplained. As an example, the wedge action which is very effective at high frequencies to decrease the stress amplitude at crack tips may diminish at lower frequencies. The crack closure at compression half cycles may be affected also by the growth of crack width due to the corrosion of crack walls, and the

wedge action seems to be greatly affected by mean stresses superimposed on alternating stresses.

The present paper deals with the fatigue crack properties in corrosive en-

Table 1 Mechanical properties of test materials.

Yield Strength σ_s (kg/mm ²)	Tensile Strength σ_B (kg/mm ²)	Elongation δ (%)	Reduction of Area ψ (%)
20	41	41	62

Table 2 Chemical compositions of test materials. (%)

C	Si	Mn	P	S
0.16	0.27	0.49	0.026	0.025

Fig. 1 Shape and dimensions of test specimens.

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vironment at various cycle frequencies to make clear the corrosion fatigue mechanism.

2. Experimental procedure

Materials tested are annealed 0.15% C-carbon steel, whose mechanical properties after the annealing and whose chemical compositions are shown in Table 1 and Table 2. The shape and dimensions of test specimens are shown in Fig. 1. The specimen A was subjected to rotating-bending fatigue and the specimen B to in-plane-bending fatigue to observe the influence of mean stresses. The specimens were annealed at 900°C for 1 h before machining. After the final machining they were annealed at 650°C for 1 h in vacuum. The stress concentration factors of the specimens A and B are 2.9 and about 6 respectively. The depth of fatigue cracks of the specimen A was continuously measured by the eddy current method, which has been reported elsewhere⁽⁶⁾. The crack depths plotted in figures are the values averaged over six points of the circumference. The depth of fatigue cracks of the specimen B was measured by the microscope on the surfaces protected from corrosion with Scotch tape, and the averaged values on both sides of specimens were used later.

A corrosive environment consisting of 1% NaCl solution in deionized water of 15 l circulated by a plastic vane pump was poured on the notched part of the specimens. The temperature of the solution was kept constant at 30°C, and flow rate at about 0.4 ~ 0.5 l/min.

3. Experimental results and considerations

The authors have reported⁽⁵⁾ that crack propagation curves can be expressed as straight lines on the figure whose ordinate is $\log l^*$, l^* being the averaged crack depth including notch depth of l_0 , and abscissa the number of stress cycles. So,

$$\log (l^*/l_0) = C_n (n - N_i) \quad (1)$$

Fig. 2 Crack growth curves.

Fig. 3 Crack growth curves.

$$dl/dn = C_n l^* \ln 10 \quad (2)$$

or

$$dl/dt = C_t l^* \ln 10, \text{ where } C_t = f C_n \quad (3)$$

are obtained.

Since the crack growth rates are expressed by C_n against stress cycles and by C_t against test duration, the behavior of crack propagation will be discussed later by C_n or C_t derived from the slopes of $\log l^* - n$ curves.

3.1 Rotating-bending corrosion fatigue

In rotating-bending crack rates were measured under the nominal stress amplitude σ_a of 13, 16, 20 and 25 kg/mm². Crack growth curves under $\sigma_a = 16$ and 20 kg/mm² are shown in Figs. 2 and 3 respectively. In air it was verified that the crack rate was unvaried at the cycle frequencies ranging from 1400 c/min to 18 c/min. As is shown in Figs. 2 and 3 the crack rate in salt water is nearly equal to or a little greater than that in air in the early stage at the frequency higher than 100 c/min, and thereafter it becomes smaller than that in air with the progress of crack propagation owing to the contribution of the wedge action. The crack initiation as well as the crack rate is also enhanced at lower frequencies.

At the frequencies lower than 2 ~ 8 c/min fatigue cracks were unable to initiate and to propagate in normal modes due to severe corrosion at notch roots, so that fatigue cracks of about 0.3 mm were initially introduced in air. At the frequencies lower than 2 ~ 8 c/min fatigue cracks were measured for the pre-cracked specimens under $\sigma_a = 13, 16, 20$ and 25 kg/mm². The results under $\sigma_a = 20$ and 25 kg/mm² are shown in Figs. 4 and 5 together with the results at high frequencies.

From these growth curves, at the low frequencies the slope C_{n1} at $l^* = 2$ mm after long duration, and at the high frequencies the slope C_{n2} in the early stage and the slope C_{n3} after the knee point in

Fig. 4 Crack growth curves.

Fig. 5 Crack growth curves.

the growth curves are adapted to discuss the crack rate. The relation between the crack growth parameter C_n and stress cycle frequency f is shown in Fig. 6, where solid lines show the trend of C_{n2} at high frequencies and of C_{n1} instead of C_{n2} at low frequencies since it was unable to obtain C_{n2} . The trends of C_{n3} after the knee point at middle and high frequencies are shown by broken lines which fall on solid lines at low frequencies since the knee point diminishes in the growth curves at the frequencies.

The value of C_{n2} increases moderately at low frequencies under the stress smaller than 16 kg/mm^2 and also under $\sigma_a = 20 \text{ kg/mm}^2$ at the frequencies higher than 8 c/min .

C_{n3} after duration for which the wedge action can be expected increases proportionately with $f^{-1/2}$ at the frequencies higher than 10 c/min , the increasing rate being faster than that of C_{n2} . The difference between C_{n2} and C_{n3} , supposedly due to the wedge action, decreases at lower frequencies and almost diminishes at the frequencies lower than 8 c/min .

Under $\sigma_a \geq 20 \text{ kg/mm}^2$ there exists a frequency range of constant C_t at low frequencies, C_{n1} being in inverse proportion to f . Under $\sigma_a = 25 \text{ kg/mm}^2$ C_{n1} inversely decreases with a decrease of frequency at frequencies lower than 0.5 c/min .

3.2 In-plane-bending corrosion fatigue

An example of crack growth curves in air is shown in Fig. 7. In general straight lines are obtained except just before final fracture. However, a knee point is observed in the growth curves especially under reversed stresses since the crack growth

Fig. 6 Relation between crack growth parameter C_n and cycle frequency f .

Fig. 7 Crack growth curves.

is enhanced in the early stage by the stress concentration due to deep and sharp notch. In addition to that slow crack growth observed in the early stage under pulsating stresses of $\sigma_m/\sigma_a = 1$.

Crack growth curves in salt water are shown in Figs. 8 and 9. At low frequencies crack is not generated in normal modes due to the intense corrosion at notch roots as was done by the rotating-bending, so that the results of the crack growth by corrosion fatigue after the pre-cracking of 0.1 mm depth in air are included in Fig. 9.

It has been already known that the crack growth in air is affected by stress amplitudes rather than by mean stresses especially under $\sigma_m/\sigma_a = 1$, and under reversed stresses implying compressive stress component crack walls bear partly the compressive load during compression cycles owing to crack closure. In consequence, the value of C_n under the reversed stress of $\sigma_a = 16 \text{ kg/mm}^2$ becomes approximately the same as that under the pulsating one of $\sigma_a = 10 \text{ kg/mm}^2$. On the other hand, in salt water at the frequencies lower than 170 c/min the crack rate under the pulsating condition of $\sigma_a = 10 \text{ kg/mm}^2$ approaches the value under the reversed one of $\sigma_a = 10 \text{ kg/mm}^2$ differing from the results in air mentioned above. This is due to the growth of crack width by intense corrosion, which makes the crack wall unable to bear the load during compression cycles under reversed condition too.

As was the case in the rotating-bending the results are discussed in terms of the slope C_{n4} and C_{n5} before and after the knee point in the growth curves. Under pulsating stresses the variances between C_{n4} and C_{n5} are considered due to the wedge action, whilst under reversed stresses the wedge action can be hardly discussed from only the variances between them since the knee point is also observed in air in this case. The relation between the crack growth parameter C_n and cycle frequency f is shown in Fig. 10. As is shown in the figure the

Fig. 8 Crack growth curves.

Fig. 9 Crack growth curves.

variance between C_{n4} and C_{n5} diminishes at $f < 10$ c/min due to a remarkable enhancement of C_{n5} with a decrease of frequency under the reversed condition of $\sigma_a = 16$ kg/mm². In the case of pulsating condition of $\sigma_a = 10$ kg/mm² also C_{n5} increases remarkably at $f < 15$ c/min, C_{n4} being equal to C_{n5} . This may be due to the decrease of the wedge action at lower frequencies, and the dominant factor promoting crack propagation is the dissolution at crack tips as was in Fig. 6.

Fig. 10 Relation between crack growth parameter C_n and cycle frequency f .

$\sigma_a = 20$ kg/mm² $\sigma_a = 20$ kg/mm² $\sigma_a = 20$ kg/mm²
(a) In air (b) In salt water (c) In salt water
 $f = 1400$ c/min $f = 8$ c/min

Fig. 11 Photographs of cross section of cracks.

3.3 Acceleration of crack growth by growth of crack width

As was mentioned before crack walls bear partly the compressive load during compression cycles due to crack closure under reversed stresses in air, whilst the compressive stresses to close crack will increase in corrosive environment since the

(a) $\sigma_a = 10$ kg/mm²
 $\sigma_m/\sigma_a = 1$
1000 c/min

(b) $\sigma_a = 10$ kg/mm²
 $\sigma_m/\sigma_a = 1$
15 c/min

(c) $\sigma_a = 16$ kg/mm²
 $\sigma_m/\sigma_a = 0$
15 c/min

↑ Direction of crack growth

Fig. 12 Photographs of fractured surfaces (in salt water).

crack width grows owing to the corrosion at crack walls. It is clear from Fig. 11 that the crack width in corrosive environment is greater at low frequencies than at high frequencies and of course than in air, which leads to an increase of the net stress amplitude promoting crack extension and to an enhancement of crack growth. As is shown in Fig. 6 the crack rate C_{n2} in the early stage is greater in salt water than in air at the frequencies lower than 450 c/min, and the differences between them are greater at lower frequencies or under smaller stresses. In comparison between reversed and pulsating conditions of Fig. 10, the influences of frequencies appear greater at $f > 15$ c/min under the reversed condition, and moreover the influences on C_{n4} without expectation of the wedge action are remarkable. These are due to the growth of crack width resulting from the corrosive removal of crack walls which is enhanced at lower frequencies under smaller stresses, i. e. at smaller crack growth parameter against time C_t .

These considerations are affirmed from fractographies. Fig. 12 (a) shows a fractured surface at 1000 c/min under pulsating stresses in salt water, which demonstrates the fatigue striation, whilst a facet pattern is observed instead of the fatigue striation at 15 c/min under pulsating stresses as is shown in Fig. 12 (b). At low frequencies under reversed stresses, however, the enhancement of corrosion due to the clashes of crack walls diminishes the pattern, which is shown in Fig. 12 (c).

To make further clear the enhanced crack growth parameter C_n due to the growth of crack width, the specimens having a thickened crack introduced by suitable repetition of stress cycles at low frequencies in salt water ahead of the pre-crack in air, which had been completely dried in vacuum for 24 h, were again subjected to reversed stresses in air. As is shown in Fig. 13 though the crack rate immediately after drying nearly equals the one in salt water at low frequencies, the recovery of load carrying capacity in compression cycle decreased the value of C_n after the subsequent crack growth of 0.2 ~ 0.3 mm in air. The decreased value of C_n is nearly equal to the one where the wedge action due to dry corrosion products can be expected. Thus the shape and dimension of crack affect

Fig. 13 Crack growth curves.
(In air-in salt water-in air)

the subsequent crack growth, the affected zone being about 0.3 mm ahead of the crack tip in the present experiment.

3.4 Wedge action due to corrosion products

The authors have reported that the crack rate in corrosive environment was decreased by the reduction in resultant range of working stress at the crack tip because the prying action of corrosion products could cause separational stress when the applied load was decreasing⁽⁵⁾. It was also observed⁽⁷⁾⁽⁸⁾ that oil had similar mechanical wedging action which reduced crack rate. The atmosphere screening effect of corrosion products will be neglected since the corrosion products of steel in salt water are very coarse, which can be proved from the fact that the crack growth parameter of C_{n3} increases remarkably with a decrease of frequencies in Fig. 6.

To clarify the detailed mechanism of the wedge action due to corrosion products, crack growth was measured after the corrosion products between crack walls were dried completely in vacuum, as shown in Fig. 14. The specimen, which had been dried in vacuum for 24 h after the cycle numbers at the knee point in the growth curves where the wedge action could be expected to be stationary, was subsequently subjected to stress cycles in air. As is shown in the figure, C_n increases immediately after the drying, which leads to the conclusion that the wedge action is attributed not to solidity but to viscous fluidity of corrosion products. However, the dried corrosion products exert a little wedge action because of the smaller value of C_n after drying than that in air.

The wedge action due to liquid corrosion products mentioned above decreases with a decrease of the value ηf where η is the viscosity of liquid, f cycle frequency as was proved in the wedge action of oil⁽⁷⁾. The remarkable enhancement of C_{n3} with a decrease of frequency from 1400 c/min and the approach of C_{n3} to C_{n2} are considered mainly due to the frequency effect of the wedge action. At the lower frequencies the growth of crack width with intensified corrosion products and the smaller rate of crack closing decrease the hydrodynamic fluid pressure due to corrosion products. The increase of the crack rate at the frequencies lower than 100 c/min can be attributed to the decrease of the wedge action and to the growth of crack width.

To make clear the relation between the crack width and the wedge action crack pro-

Fig. 14 Crack growth curves.
(In salt water- in air)

pagation in salt water has been compared between the specimen subjected to stress repetitions from the start and the one pre-cracked in air to a depth of 0.4 mm. As is shown in Fig. 15 the slope for the pre-cracked specimen subsequently stressed in salt water (solid line) is smaller from the start than that in air which equals the slope before the knee point of the broken lines, and the short time corrosion exerts the wedge action in extremely narrow crack width. To exemplify this a pre-cracked specimen subsequently stressed in salt water at high frequency for short time of 36 min was dried in vacuum for 24 h, and thereafter the specimen was again subjected to stress repetitions in air. The result is shown in Fig. 16, in which the cycle frequency at the intermediate stage of corrosion fatigue is higher than that in Fig. 13. As is shown in the figure the wedge action due to corrosion products remains even after drying and the slope C_n is unvaried before and after drying. However, the slope C_n gradually increases with the lapse of testing to the value of the specimen stressed from the start in air after considerably long time. In very narrow cracks like those introduced in air extremely short time corrosion decreases the crack rate, which corresponds to the unvaried crack rate before and after drying for a while. In this case, therefore, the wedge action is considered to be attributed to a small amount of corrosion products as solid.

It is clear from Fig. 2 that the induc-

Fig. 15 Crack growth curves.
(In salt water, In air-in salt water)

Fig. 16 Crack growth curves.
(In air-in salt water-in air).

ing period is necessary until a given amount of corrosion products or more exerts an effective wedge action as fluid. However, in very narrow crack width a small amount of corrosion products exerts the wedge action as solid without the inducing period. As is shown in Fig. 15, the wedge action due to solidity of corrosion products interchanges the primary one due to fluid pressure of the products with the progress of stress cycles.

Thus the wedge action can be classified into the following three types :

(i) The wedge action due to solidity of corrosion products, which is effective only in the extremely narrow cracks like those in air, (ii) the wedge action due to hydrodynamic fluid pressure of corrosion products, and (iii) the wedge action due to dry corrosion products.

3.5 Acceleration of crack growth due to dissolution of crack tips

As was shown in Fig. 6 under the rotating-bending the value of C_{n1} increases remarkably at the frequency range of $2 \sim 0.5$ c/min under $\sigma_a = 25$ kg/mm², and also at the range of $2 \sim 0.28$ c/min under $\sigma_a = 20$ kg/mm², and C_t tends to become constant. This tendency is observed at $1 \sim 10$ c/min under pulsating stresses under the in-plane-bending, which was shown in Fig. 10. However, at the further low frequencies C_n tends to a constant value at about 0.5 c/min under $\sigma_a = 25$ kg/mm² in Fig. 6 and also at the frequencies lower than 1.4 c/min under reversed stresses of $\sigma_a = 16$ kg/mm² in Fig. 10.

The fact that the constant C_t appears with the decreased frequency is due to the remarkable influences of time factor on crack growth. Gallagher reports that dl/dt becomes constant under $K_{max} > K_{ISCC}$ and dl/dn constant under $K_{max} < K_{ISCC}$ at extremely low cycle frequencies in the low cycle fatigue test of ultra-high-strength 4340 steel in sea water⁽⁹⁾. However, the direct comparison of the present results with the work by Gallagher is impossible, since the material used in the report was a brittle high-strength material sensitive to stress corrosion cracking in sea water, and the crack rate was $10 \sim 10^2$ times greater than that in the present experiment.

Crack tip propagating at small crack rate in corrosive environment has in general an opening angle of about 90 degrees, which is composed of two planes inclined 45 degrees to the growth direction of crack tip, as is shown in Fig. 17. The shape is very similar to the crack tip model, in which fatigue cracks are supposed to propagate by the repetition of slip deformation directed to 45 degrees to principal stresses⁽¹⁰⁾, and the propagation of this kind of cracks is known to be due to the electrochemical dissolution enhanced by the slip motion at crack tips. As is shown in Fig. 18 the enhanced dissolution by the slip motion can be proved from the crack width in pearlite being smaller than in ferrite.

The authors have reported on the influences of stress wave forms in low cycle corrosion fatigue and made clear that the frequency effect in low cycle range was

due to the lag of corrosion potential to strain^{(2)~(4)}. The remarkable enhancement of crack rate is due to the dissolution of crack tips accelerated by a decrease in the lag of corrosion potential to strain. According to the reports, moreover, the damaging effect of varying stress in one stress cycle was remarkable, which coincides with the fact that the dominant factor in crack growth is the dissolution of moving slip lines at crack tips.

Since dissolution of slip lines is controlled by the characteristic of corrosion potential following the strain, the maximum value takes place at the frequency where the full following is obtained, and thereafter the frequency effect disappears, C_n being constant. These changes of crack rate coincide in nature with the reported frequency effect⁽¹⁾ on the life of corrosion fatigue of the materials insensitive to stress corrosion cracking.

At the frequency lower than that of constant C_n there occurs a case where C_n inversely decreases at $f < 0.5$ c/min under $\sigma_a = 25$ kg/mm² as is shown in Fig. 6. This is due to the remarkable branching of crack tips, which is shown Fig. 19, and this kind of branching could not at all be observed in the specimens under $\sigma_a = 20$ kg/mm² where no decrease of C_n occurred until $f = 0.28$ c/min.

(a) $\sigma_a = 16$ kg/mm²
 $f = 0.5$ c/min

(b) $\sigma_a = 25$ kg/mm²
 $f = 0.5$ c/min

Fig. 17 Photographs of crack tips.

Intergranular cracking as is shown in Fig. 20 was frequently observed under the condition of small crack growth parameter against time C_t . Since the intergranular crack is thinner than the transgranular one, and the crack rate is considered greater in the former than in the latter, the intergranular cracking may partly enhance crack rate in low frequency range.

Facet patterns at low frequencies under pulsating stresses as was shown in Fig. 12 and the turning of the crack tip direction

$\sigma_a = 20$ kg/mm², $f = 2$ c/min

Fig. 18 Photographs of cross section of cracks.

$\sigma_a = 25$ kg/mm², $f = 0.28$ c/min

Fig. 19 Photographs of crack tips.

$\sigma_a = 13$ kg/mm², $f = 8$ c/min

Fig. 20 Photographs of crack tips

at the boundary between pearlite and ferrite as was shown in Fig. 17 (b) explain that the crack growth is caused by the corrosion dissolution along slip planes of crystals. These kinds of facets are quite different from those by stress corrosion cracking of the material sensitive to stress corrosion cracking subjected to low cycle corrosion fatigue⁽⁴⁾, though the shapes are similar to each other. At low cycle frequency under reversed stresses the facet pattern diminishes owing to the enhancement of corrosion due to the clashes of crack walls mentioned before.

4. Conclusions

Corrosion fatigue test of a mild steel in saline has been carried out at various cycle frequencies ranging from 1400 c/min to 0.28 c/min to study corrosion fatigue mechanism.

At the cycle frequencies from 1400 c/min to 100 c/min, the decreases of the wedge action due to the hydrodynamic pressure of corrosion products are predominant for the increase of crack rate at lower cycle frequencies. The wedge action becomes more effective for the more narrow cracks and the greater closing rate of cracks. At the frequencies from 100 c/min to several cycles per minute, the wedge effect mentioned above becomes negligibly small, and the growth of crack width due to the corrosion of crack walls increases the crack rate at lower frequencies. In consequence the frequency effect in this range appears greater under smaller stress amplitudes where the crack rate is rather small and moreover under compressive stresses in one cycle. At the cycle frequencies lower than several cycles

per minute, the dissolution of crack tips dominantly increases the crack rate, the crack growth parameter against time being constant. However, at extremely low frequencies a decrease of crack rate is sometimes caused by a remarkable branching of crack tips.

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