The Influence of Crack Length on SCC Crack Growth Behavior of High-Strength Steel under Dynamic Loading Conditions*

Kohji MINOSHIMA**, Tadashi SUGIYAMA***
and Kenjiro KOMAI**

The influences of crack length on the crack growth in stress-corrosion-cracking (SCC) of 523 K-tempered, high-strength steel, SCM435H ($\sigma_B=1\ 770$ MPa) immersed in a 3.5% NaCl solution were investigated under dynamic loading conditions; static SCC under a sustained load, dynamic SCC under a sustained load with high frequency vibratory stresses superimposed, and cyclic SCC under low-frequency variation. Threshold values of static and dynamic SCC of short cracks, whose crack length from notch root, l , ranged from 1.52 mm to 2.81 mm, were smaller than those of long cracks ($l=6.86-9.78$ mm). Dissolution of the fracture surface was more prevalent in short cracks than in long cracks, and a decrease in threshold values of short cracks is considered to be caused by increased hydrogen uptake at the crack tip associated with the accelerated dissolution of fracture surfaces compared to long cracks. Crack growth rates of short cracks ($l \leq 6.5$ mm) at the plateau region were also accelerated compared to those of long cracks ($l > 6.5$ mm). Static SCC crack growth rates of long cracks were accelerated and the threshold value was lowered by deaeration of the solution. However, the deaeration had no influence on the crack growth rates of static SCC of short cracks. In the case of cyclic SCC at $R=0.1$, no influence of crack length ($l > 1.18$ mm) on crack growth rates was observed. But at $R=0.5$, crack growth rates of short cracks were accelerated compared to those of long cracks.

Key Words: SCC, Static SCC, Dynamic SCC, Cyclic SCC, Crack Length, Short Crack, Hydrogen Embrittlement, High-Strength Steel

1. Introduction

High-strength materials are sensitive to environment, and environmentally induced degradation of materials including stress corrosion cracking (SCC), poses key considerations of fracture control design and maintenance for machines and structures. Therefore, we must clear the mechanisms of environmentally induced degradation of materials and establish the basis of machine design. It is well known that fracture mechanics provides a quantitative tool for correlating SCC crack growth rates⁽¹⁾, though most investigations have focused on long-crack growth behavior using CT specimens. Recently, however, the importance of short-crack growth behavior has been accentuated because

the life of smooth specimens is considered to be dominated by periods of crack initiation and the growth stage of short cracks. Especially in a corrosive environment, cyclic stress corrosion crack growth rates of short cracks have been reported to be accelerated compared to those of a fully long cracks, even though the cracks are regarded as long cracks from the mechanical and/or microstructural standpoints (~ 2 mm)^{(2),(3)}.

In this investigation, the influences of crack length on static stress corrosion crack growth under a sustained load, dynamic stress corrosion crack growth under a sustained load with the superposition of high-frequency, small vibratory loads⁽¹⁾, and cyclic stress corrosion crack growth under low-frequency variation⁽¹⁾ are investigated in a high-strength steel/3.5% NaCl solution system sensitive to a hydrogen embrittlement (HE) type of SCC. The mechanisms of the acceleration of a short crack in corrosive environment are discussed.

* Received 19th January, 1990. Paper No. 88-0750A

** Department of Mechanical Engineering, Kyoto University, Yoshidahonmachi, Sakyo-ku, Kyoto, 606, Japan

*** Sumitomo Electric Co., 5-15, Kitahama, Higashi-ku, Osaka, 541, Japan

2. Experimental Procedures

The material tested was a high-strength steel, JIS SCM 435 H. The chemical composition, heat treatments, and mechanical properties are respectively shown in Tables 1 to 3. The test specimens, single-notch, four-point-bending specimens shown in Fig. 1, were machined into L-R orientation. The notches of 0.5 mm length and 0.2 mm width were introduced by electrical discharge machining.

The test environment was a 3.5% NaCl solution, which was prepared with deionized water (specific electric resistance $>1 \text{ M}\Omega \cdot \text{cm}$). The dissolved oxygen was controlled and divided into an aerated solution ($\text{DO} > 6.1 \text{ ppm}$) and a deaerated one ($\text{DO} < 0.2 \text{ ppm}$) by introducing N_2 gases. The solution was kept at $298 \pm 0.5 \text{ K}$. The experiments were done under the free-corrosion conditions. The specimens' surfaces were coated with transparent tape to protect the specimen surfaces from corrosion in order to observe crack growth. Therefore, the solution acted only on crack walls and a crack tip.

In this investigation, the following tests were performed; static SCC under a sustained load, dynamic SCC under high-frequency sinusoidal vibra-

Table 1 Chemical composition of the material tested, JIS SCM435H.

C	Si	Mn	P	S	Cu	Ni	Cr	Mo
0.36	0.19	0.71	0.030	0.011	0.07	0.05	0.99	0.16

Table 2 Heat treatments of the material tested, JIS SCM435H.

Normalizing	Quenching	Tempering
1143K 1hr. AC	1128K 1hr. OQ	523K 1hr. WC

Table 3 Mechanical properties of the material tested, JIS SCM435H.

0.2% Yield Strength	Tensile Strength	Elongation
1380MPa	1770MPa	13%

Fig. 1 Shape and dimensions of test specimens. All dimensions are in mm. Arrows show the loading points.

tory loads at a stress ratio, R , of 0.9 and a stress cycle frequency, f , of 30 Hz, and cyclic SCC under low-frequency ($f=0.1 \text{ Hz}$) triangular loads at $R=0.1$ and 0.5. The experiments were performed after a test specimen was immersed in the solution for more than 48 hours. Most of the experiments were run under stress intensity factor (K_I) increasing conditions. However, in the neighborhood of thresholds, the tests were performed under K_I -decreasing conditions by lowering the load little by little. The threshold values were obtained when no change of crack length was observed for more than 48 hours. In the case of cyclic SCC tests, crack-opening stress intensity factor, K_{op} , was measured by the unloading elastic compliance technique with back-surface strain gauges. The fracture surfaces were examined by a high-resolution scanning electron microscope after the surfaces were cleaned by 1% HCl+0.1% inhibitor solution.

3. Experimental Results and Discussion

3.1 Static and dynamic stress corrosion crack growth behavior

3.1.1 Crack growth rates Figure 2 illustrates the relationship between crack growth rates versus time, da/dt , and the maximum stress intensity factor, K_{max} , of a long crack. The crack length from a notch root, l , in aerated solution was longer than 6.86 mm in static SCC and 6.72 mm in dynamic SCC; in deaerated solution it was longer than 9.78 mm in static SCC.

It is clear from Fig. 2 that the threshold value of dynamic SCC, K_{DSCC} , was lowered from that of static SCC, K_{ISCC} , by small vibratory loads. We must note that such small vibratory loads affect the threshold

Fig. 2 Relation between K_{max} and da/dt of static and dynamic SCC of a long crack.

values of SCC. K_{ISCC} in deaerated solution was smaller than that in aerated solution. However, in the plateau region, where crack growth rates are independent of K_{max} , influences of small vibratory loads and deaeration of solution were not observed.

Figures 3 and 4 show the results of K_{max} - da/dt and l - da/dt obtained by short-crack experiment. The superscript, "*", in Fig. 4 indicates that crack growth rates were dependent on K_{max} , i.e., Region I. Crack length, l , in short-crack experiments in aerated solution ranged from 1.12 mm to 11.92 mm for static SCC, and from 1.52 mm to 9.02 mm for dynamic SCC, and l in deaerated solution from 2.81 mm to 10.19 mm for static SCC. Table 4 summarizes the threshold values,

Fig. 3 Influences of crack length on crack growth rates of static and dynamic SCC.

Fig. 4 Relation between da/dt and crack length of static and dynamic SCC.

for da/dt being smaller than 3.0×10^{-10} m/s and the crack length.

Compared with the results of the same experimental conditions, the threshold values of short cracks ($1.52 \text{ mm} \leq l \leq 2.81 \text{ mm}$; Table 4) were smaller than those of long cracks ($6.86 \text{ mm} \leq l$). This means that threshold values are dependent on crack length. As in the cases of long cracks shown in Fig. 2, small vibratory loads lowered the threshold values, resulting in K_{ISCC} values smaller than K_{ISCC} values. We must note that small vibratory loads also affected the threshold values of small cracks. However, the influences of deaeration of solution on K_{ISCC} were not observed.

As for the plateau region, long-crack data had one unique plateau, whereas short-crack data had two plateaus; da/dt under lower K_{max} was higher than that under higher K_{max} (see Fig. 3). Figure 4 shows that these higher plateau crack growth rates were brought about when l was smaller than 6.5 mm. When $6.5 \text{ mm} < l < 7.5 \text{ mm}$, da/dt gradually decreased and equaled da/dt by long-crack experiments when $l > 7.5 \text{ mm}$. The reason why short-crack experiments had two plateaus, shown in Fig. 3, was that crack length at lower K_{max} the was smaller than that at higher K_{max} . The crack growth rate in the plateau region depended on the crack length.

Gangloff and Turnbull⁽⁴⁾ have investigated the influences of crack length on K_{ISCC} by the rising-load method, and have concluded that the influence of crack length is marked when $l < 1 \text{ mm}$, resulting in lower K_{ISCC} for short cracks than for long cracks. In this investigation, influences of crack length were observed in $1.52 \text{ mm} \leq l \leq 2.81 \text{ mm}$ for threshold values and in $l < 6.5 \text{ mm}$ for da/dt in the plateau region. Further investigations are necessary to determine the limit value of crack length where the acceleration of crack growth occurs. Here, we designate short-crack when $l \leq 6.5 \text{ mm}$ and long crack when $l > 6.5 \text{ mm}$.

3.1.2 Fracture surface morphology Figures 5 and 6 show the near-threshold fracture surfaces of static SCC of short and long cracks in aerated and

Table 4 Threshold values and crack length of static and dynamic SCC.

	SCC Aerated soln.		SCC Deaerated soln.	DSCC Aerated soln.
Long crack ($\text{MPa} \cdot \sqrt{\text{m}}$)	24.1	24.3	18.4	13.1
l (mm)	6.86	7.39	9.78	8.12
Short crack ($\text{MPa} \cdot \sqrt{\text{m}}$)	13.4	15.7	14.1	9.28
l (mm)	2.66	2.21	2.81	1.52

deaerated solution, respectively. Figure 7 shows the fracture surfaces at near-threshold of dynamic SCC. Irrespective of crack length and testing condition, fracture surfaces were predominantly covered with intergranular cracking. However, the most marked differences existed in dissolution. In Figs. 5 and 6, the dissolution of fracture surfaces was more predominant in short cracks, shown in (a), than in long cracks, shown in (b). This tendency of dissolution was more remarkable in dynamic SCC; see Fig. 7. Dissolution of fracture surfaces was suppressed by the deaeration of solution in both long and short cracks. The differences in dissolution of fracture surfaces between short and long cracks were caused only by the dissolution during crack growth period, not by differences of immersion time, which was confirmed by interrupted tests.

Dissolution of fracture surfaces was quantified as follows: the most severely dissolved fracture surface of dynamic SCC of a short crack in aerated solution (Fig. 7) gains the factor "5", and the least dissolved one of static SCC of a long crack in deaerated solution

(Fig. 6(b)), "1". The severity in the dissolution of fracture surfaces was measured using this scale. The results are shown in Table 5. It is clear that fracture surfaces of short cracks were more severely dissolved than those of long cracks, that small vibratory loads accelerated the dissolution, and that deaeration of the solution suppressed the dissolution.

3.1.3 Influences of crack length Compared at the same testing conditions, threshold values of short cracks were smaller than those of long cracks, at the same time, dissolution of fracture surfaces was more prevalent in short cracks than in long cracks. The decrease in threshold values by decreasing crack length corresponded to the increase in the severity of fracture surface dissolution.

At the free-corrosion potential, hydrogen which enters and embrittles the materials is considered to originate from the dissolution reaction. As was shown in Table 5, dissolution of fracture surfaces was promoted, which means that hydrolysis of metal ion was more promoted in short cracks, resulting in a higher H^+ concentration within a crack, *i. e.*, lower

(a) short crack ($l=2.7$ mm, $K_I=13.4$ MPa·m^{1/2})

(b) long crack ($l=6.8$ mm, $K_I=24.1$ MPa·m^{1/2})

Fig. 5 Near-threshold fracture surfaces of static SCC in aerated solution. Arrow shows the crack growth direction.

(a) short crack ($l=2.8$ mm, $K_I=15.4$ MPa·m^{1/2})

(b) long crack ($l=9.7$ mm, $K_{max}=18.4$ MPa·m^{1/2})

Fig. 6 Near-threshold fracture surfaces of static SCC in deaerated solution. Arrow shows the crack growth direction.

pH values. In the case of a short crack, a decrease in pH within a crack increased the hydrogen content at the crack tip, resulting in a decrease in threshold values and an increase in da/dt .

In aerated solution, K_{DSCC} was smaller than K_{ISCC} . In this case, small vibratory loads promoted the fatigue failures of oxide films at the crack tip, which led to a decrease in pH value within a crack by accelerated dissolution reaction and also helped hydrogen enter the embrittled region of the material⁽¹⁾. Therefore, the hydrogen content in dynamic SCC was increased, which in turn decreased the threshold values of dynamic SCC from static SCC. The fracture surfaces also supported the above-mentioned discussions (see Table 5).

3.1.4 Influences of deaeration In the case of static SCC or dynamic SCC at a high-stress ratio, the transportation of environmental species to and from the inside and outside of a crack ($l \geq 1.12$ mm) is mainly controlled by diffusion⁽⁵⁾, excepting the migration due to the potential difference of ionic species, and the crack tip at the crack length is reported to be deaerated⁽⁶⁾. Therefore, the influences of differences in dissolved oxygen concentration in bulk solution are ignored at the crack tip. However, the threshold value of static SCC of a long crack was lowered by deaeration, whereas no influence was observed for a short crack. This was explained by the competition of two effects, a retardation effect and an acceleration effect.

Table 5 Dissolution of fracture surface at near-thresholds of static and dynamic SCC.

	SCC Aerated soln.	SCC Deaerated soln.	DSCC Aerated soln.
Long crack	2	1	4
Short crack	4	2	5

Fig. 7 Near-threshold fracture surface of dynamic SCC of a short crack in aerated solution. Arrow shows the crack growth direction. ($l = 1.53$ mm, $K_{max} = 9.3$ MPa $\cdot$ m^{1/2}).

In the deaerated condition, the oxygen-reduction reaction on the outside of a crack is suppressed, which leads to a decrease in the dissolution-reaction rate within a crack. This will bring about the retardation effect by decreasing hydrogen content at the crack tip. At the same time hydrogen evolution reaction within a crack occurs instead of oxygen reduction reaction, which will bring about the acceleration effect by increasing hydrogen content.

In the case of a short crack, the suppression of surface dissolution by deaeration was more prevalent than for a long crack. That is, the retardation effect was stronger than for a long crack, and therefore the retardation effect canceled out the acceleration effect. Thereby no influence of deaeration on thresholds was observed. In the case of long cracks, on the other hand, the suppression of surface dissolution by deaeration was weaker, and the retardation effect was smaller compared to the case of short crack. Besides the long crack had a wider cathodic area, i.e., crack walls which, in turn, made the acceleration effect more effective compared to the case of a short crack. Therefore, the acceleration effect overcame the retardation effect, resulting in a decrease in threshold value for the long crack.

3.2 Cyclic stress corrosion crack growth behavior

3.2.1 Crack growth rates Figure 8 shows the relationship between stress intensity factor range, ΔK , and cyclic stress corrosion crack growth rates, da/dN , which were obtained by "short crack" and "long crack" experiments. The crack length from a notch root for short-crack experiments varied as follows: $1.18 \text{ mm} < l < 6.91 \text{ mm}$ for $R=0.1$ and $0.61 \text{ mm} < l < 4.87 \text{ mm}$ for $R=0.5$ in aerated solution; $1.44 \text{ mm} < l < 5.62 \text{ mm}$ for $R=0.1$ in deaerated solution. The crack length for the long-crack experiment was: $l > 6.49 \text{ mm}$ for $R=0.1$ and $l > 5.96 \text{ mm}$ for $R=0.5$ in aerated solution; $l > 5.66 \text{ mm}$ for $R=0.1$ in deaerated solution.

At $\Delta K \leq 20 \text{ MPa} \cdot \text{m}^{1/2}$, da/dN for short crack experiments was higher than that for long crack experiments. Irrespective of crack length, no acceleration by deaeration was observed. As for a stress ratio effect, da/dN at $R=0.5$ for both short and long crack

Table 6 Dissolution of fracture surface at near-thresholds of cyclic SCC.

	$R=0.1$ Aerated soln.	$R=0.1$ Deaerated soln.	$R=0.5$ Aerated soln.
Long crack	2	1	1
Short crack	5	3	4

experiments was higher than that at $R=0.1$.

The crack closure was observed only in a long-crack experiment at $R=0.1$. Figure 9 shows the relationship between da/dN and the effective stress intensity factor range, ΔK_{eff} , which was deduced by $\Delta K_{eff} = K_{max} - K_{op}$. Here, K_{op} is a crack opening stress intensity factor range. In terms of ΔK_{eff} , the results at $R=0.1$ were not influenced by crack length, which was larger than l of 1.18 mm; crack growth rates were uniquely determined by the applied effective stress intensity factor range. In other words, the acceleration of a short crack at $R=0.1$ from a long crack, which was observed in terms of ΔK (Fig. 8), was due to the crack closure. At $R=0.5$, on the other hand, no crack closure was observed for both short and long crack experiments, and da/dN for the short crack experiment was about 5 to 100 times faster than that for the long crack experiment. We must note that

da/dN of a short crack accelerated, compared to a long crack when an applied stress ratio was high as $R=0.5$.

3.2.2 Fracture surface morphology Fracture surfaces of near-threshold regions of short and long crack experiments in aerated solution are shown in Fig. 10 ($R=0.5$) and Fig. 11 ($R=0.1$). As in static and dynamic SCC, which was already shown in Figs. 5~7 and Table 5, the surface dissolution of short cracks was more prevalent than that of long cracks. As in Table 5, the severity of dissolution was quantified: the most severely dissolved fracture surface (Fig. 11(a), $R=0.1$) gains "5", and the least (Fig. 10(b)), "1". The results are shown in Table 6. From the table, it is clear that fracture surfaces of short cracks were severely dissolved than those of long cracks and that the deaeration of solution suppressed the fracture surface dissolution.

Fig. 8 Influences of crack length on cyclic stress corrosion crack growth rates, da/dN in terms of ΔK .

Fig. 9 Influences of crack length on cyclic stress corrosion crack growth rates, da/dN in terms of ΔK_{eff} .

(a) short crack ($l=0.90$ mm, $\Delta K_{eff}=8.5$ MPa·m^{1/2})

(b) long crack ($l=6.00$ mm, $\Delta K_{eff}=9.2$ MPa·m^{1/2})

Fig. 10 Near-threshold fracture surfaces of cyclic SCC at $R=0.5$ in aerated solution. Arrow shows the crack growth direction.

(a) short crack ($l=1.50$ mm, $\Delta K_{eff}=10.0$ MPa $\cdot$ m $^{1/2}$)

(b) long crack ($l=6.48$ mm, $\Delta K_{eff}=7.3$ MPa $\cdot$ m $^{1/2}$)

Fig. 11 Near-threshold fracture surfaces of cyclic SCC at $R=0.1$ in aerated solution. Arrow shows the crack growth direction.

The fracture surfaces, except at $R=0.5$ of a short crack in aerated solution, were a mixed mode of intergranular failures and transgranular failures. At $R=0.5$ of a short crack, however, intergranular failures, which were heavily attacked by dissolution shown by an arrow "a" in Fig. 10(a), were dominant, and transgranular failures shown by an arrow "b" in Fig. 10(a) were scarcely observed. This fracture-surface morphology corresponded well to the high acceleration at $R=0.5$ of short cracks.

4. Conclusions

The influences of crack length on static, dynamic, and cyclic stress corrosion (HE) crack growth behavior were investigated in a high-strength steel, JIS SCM 435 H in 3.5% NaCl solution, and the following were made clear:

(1) In cases of both static and dynamic SCC, threshold values of short cracks ($l=1.52-2.81$ mm) were lower than those of long cracks ($l=6.86-9.78$ mm). The dissolution of fracture surfaces was more prevalent in short cracks than in long cracks, and a decrease in thresholds was considered to be caused by increased hydrogen uptake at the crack tip associated with accelerated dissolution of fracture surfaces.

(2) Crack growth rates of short cracks ($l \leq 6.5$ mm) in the plateau region were also accelerated compared to those of long cracks ($l > 6.5$ mm).

(3) As in the cases of long cracks, the threshold values of dynamic SCC, K_{DSCC} , of short cracks ($l=1.52-2.81$ mm) decreased from those of static SCC, K_{ISCC} , by the superposition of small vibratory stresses on a sustained load.

(4) Deaeration of the solution made the threshold value of K_{ISCC} of long cracks ($l=6.86-9.78$ mm) decrease. However, no influence of the deaeration on K_{ISCC} of a short crack ($l=2.21-2.81$ mm) was observed. This was explained by the competition between

the acceleration and the deceleration effect by deaeration.

(5) In the case of cyclic SCC, crack growth rates in terms of ΔK of a short crack were accelerated from those of a long crack. In terms of ΔK_{eff} , however, no influence of crack length ($l > 1.18$ mm) on crack growth rates at $R=0.1$ was observed. But at a high-stress ratio of $R=0.5$, crack growth rates of a short crack were accelerated compared to those of a long crack, even in terms of ΔK_{eff} .

References

- (1) Komai, K. and Minoshima, K., Dynamic and Cyclic Stress Corrosion Cracking of Metals, Advanced Mater. for Severe Service Appl., (Ed. Iida, K. and McEvily, A. J.), (1987), p. 373, Elsevier Applied Science.
- (2) Gangloff, R. P., Crack Size Effects on the Chemical Driving Force for Aqueous Corrosion Fatigue, Metall. Trans., A, Vol. 16, No. 5(1985), p. 953.
- (3) Nakajima, M. and Kato, Y., The Effect of Cyclic Frequency on Short Crack Growth Behavior of High Strength Steel in a Corrosive Environment, Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 54, No. 504(1988), p. 1467.
- (4) Gangloff, R. P. and Turnbull, A., Crack Electrochemistry Modeling and Fracture Mechanics Measurement, Modeling Environmental Effects on Crack Growth Process, (Ed. Jones, R. H. and Gerberich, W. W.), (1985), p. 55, Metallurg. Soc. Inc.
- (5) Turnbull, A. and Thomas, J. G. N., A Model of Crack Electrochemistry for Steels in the Active State Based on Mass Transport by Diffusion and Ion Migration, J. Electrochem. Soc., Vol. 129, No. 7 (1982), p. 1412.
- (6) Turnbull, A., Theoretical Evaluation of the Dissolved Oxygen Concentration in a Crevice or Crack in a Metal in Aqueous Solution, Br. Corros. J., Vol. 15, No. 4 (1980), p. 162.