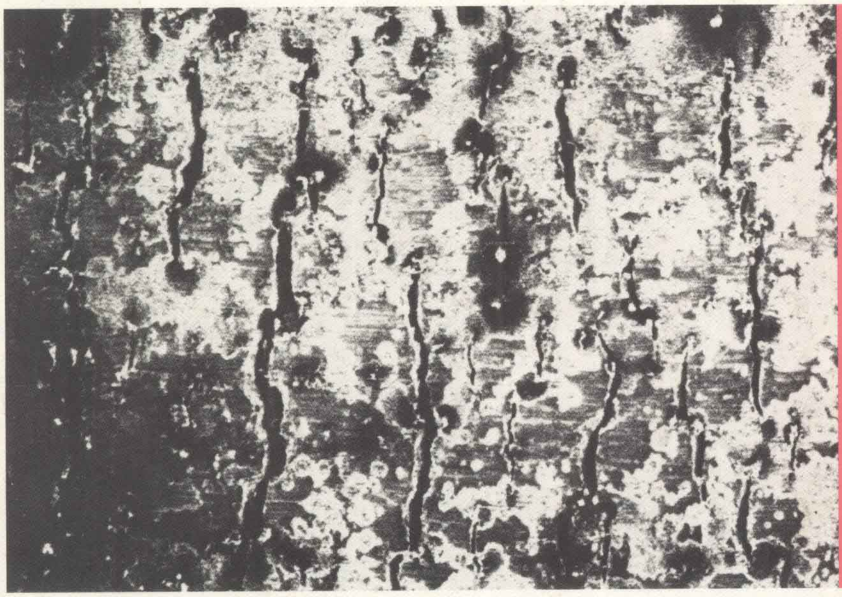
Corrosion Cracking

Edited by V.S. Goel

Conference Proceedings



American Society for Metals

CORROSION CRACKING

Proceedings of the Corrosion Cracking Program and Related Papers presented at the International Conference and Exposition on Fatigue, Corrosion Cracking, Fracture Mechanics and Failure Analysis

2–6 December 1985
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Edited by
V. S. Goel

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FOREWORD

This volume contains part of the total number of papers presented at the "International Conference on Fatigue, Corrosion Cracking, Fracture Mechanics and Failure Analysis," held in Salt Lake City, Utah, USA, from 2-6 December 1985. Response to this conference was so good that it resulted in a large number of papers. To satisfy the needs of different interest groups and to keep the proceedings of the conference in a manageable form, it was decided to publish it in four separate volumes:

Analyzing Failures: The Problems and The Solutions
Corrosion Cracking
The Mechanism of Fracture
Fatigue Life: Analysis and Prediction

The above paper collection volumes may be obtained from the American Society for Metals. This conference covered a wide range of topics, some of fundamental interest and some of application interest. To facilitate an early publication, the editing has been kept to a minimum. We hope the the technical merits of the papers outweigh any grammatical or minor stylistic deficiencies.

The advances in the concepts of design are pushing the operational limits of engineering materials and so maximum performance is expected out of the materials. Due to the general economic crunch, almost everyone wants the maximum life out of their equipment. The electric utilities want their plants to run more than the designed plant life (mostly 40 years), aircraft companies want their planes to fly longer, the transportation industry wants that its bridges last indefinitely, and the chemical industry wants their plants to keep on producing products. There is also an increased awareness on the part of the public for safety and reliability of components, because failure of components in large aircraft, nuclear plants or other large structures can lead to large-scale disasters like the Bhopal tragedy in India, the Three Mile Island accident in the USA and the string of airline disasters in 1985.

All of this shows that today materials are expected to show maximum performance, provide long life for maximum economy and at the same time ensure safety and reliability of components and systems. For all this, we need to understand the materials better and apply the principles of fracture mechanics, corrosion and fatigue to the solution of practical problems. This conference was planned to provide a forum for the exchange of ideas and allow a better understanding of the theory and applications of the materials science which can ensure safety in combination with the expected life and performance goals for materials.

The theme of this conference was "Technology Transfer" among the various groups who apply theory to the application of practical problems. There are many specialized meetings in this area which permit workers to come together and discuss problems in their specific application areas. However, there is no single meeting or conference which brings together workers in the various application areas such as Aerospace structures, Army-Navy Applications, Bridges and Architectural Structures, Transportation Industry and Nuclear Industry to learn what is being done in other areas which they may be able to utilize to their advantage. This conference was aimed at bringing together workers from different applications areas to give them a wider perspective. Hence, this conference was of interest to engineers, metallurgists and also to the engineering managers who remain concerned about product failure and liability.

The success of this conference was based on the contributions of the speakers, session chairmen and members of the Technical Review Committee and the Organizing Committee who generously supported this Conference. I would like to thank all the participants on behalf of the American Society for Metals and the co-sponsoring societies for their generous contribution of time and effort towards the success of this Conference.

Dr. V. S. Goel
Chairman, Organizing Committee

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Effects of Frequency, Stress Rising Time and Stress Hold Time on Corrosion Fatigue Crack Growth Behaviour of Low Alloy Cr-Mo Steel

By

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ABSTRACT

For da/dN under 3.5% NaCl solution in low alloy Cr-Mo steel, the experiment were carried out, stress frequency f being controled by stress rise time t_R and stress hold time t_H as well, in order to clear whether da/dN depends on cycle only, or on time only or on both cycle and time. From the results and the analysis, a new experimental formula was obtained for da/dN in terms of f, t_R or t_H non-linearly. A line of considerations as stochastic process is proposed for the significance of the equation of this type, and as a special case da/dN and da/dt in corrosion fatigue (t_H=0) are characterized in terms of frequency dependence.

INTRODUCTION

There have been many literatures[1)-6)] on the effect of stress rise time t_R, stress hold time t_H and frequency f on crack propagation rate under corrosive condition. It, however, appears to have been no systematic studies at the point of that each of these factors can be chosen independently and thus formulated. The present study is one for that purpose and a continuation of our studies[7)8)] on the problems. Frequency being controled by t_H and t_R as well, the experiments were carried out and based on the analysis of the results, a new experimental formula for da/dN under corrosive condition is proposed in non-linear terms of frequency f, stress rise time t_R and stress hold time t_H. A line of consideration as stochastic process is proposed for the significance of the equation of this type, and as a special case da/dN and da/dt in corrosion fatigue (t_H=0) are characterized in terms of frequency dependence.

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MATERIALS AND SPECIMEN USED

The specimen used is low alloy Cr-Mo steel, and the chemical composition is shown in TABLE 1. It was machined as shown in Fig. 1, and then oil tempered after heating for 10min. at 850°C in salt bath, and water quenched after heating for 60min. at 520°C. Static mechanical properties is shown in TABLE 2. After heat treatments, the slit of 0.3mm width and 2mm depth was provided by crystal cut at one side of the specimen. The specimen surface was grounded by #6~2,000 emery paper, and then polished by buffing with cromium oxides.

TESTING APPARATUS AND METHOD

In the present testing machine, stress rising time t_R and stress hold time t_H can be selected independently, that is, the stress frequency f can be controled by t_H and t_R as well. The testing machine of cantilever type was used. Examples of the stress wave realized by this machine are shown in Fig. 2. A sine wave was used for fatigue, and therefore, the stress gradient with respect to time equals to zero at the instant when maximum tensile stress σ_{max} is reached, and, thus, the shock effect can be avoided. 3.5% NaCl water as soluted in distillated one was used. Test specimen temperature and pH was kept as 18.0 ± 3.0°C and 6.3 ±

TABLE 1. Chemical Composition (wt%)

C	Si	Mn	P	S	Cr	Mo
0.38	0.34	0.84	0.018	0.004	1.07	0.17

TABLE 2. Static Mechanical Properties

NPa		%	
Yield Stress	Ultimate tensile strength	Elongation	Reduction of area
1140	1187	11	37

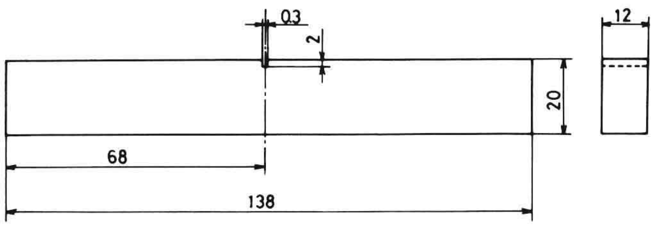

Fig. 1. Specimen shape and dimension for stress corrosion cracking and corrosion fatigue. (in mm)

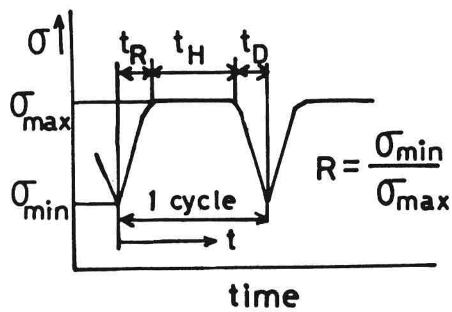

Fig. 2. Stress wave used.

0.2, throughout testing, respectively. The crack length was continuously measured by the microscope with the magnification of twenty times. The stress intensity factor was calculated by the following equation:[9)]

$$K = \frac{6M\sqrt{a}}{BW^2}\ Y \qquad (1)$$

where

$$Y = \left\{1.99 - 2.47\left(\frac{a}{W}\right) + 12.97\left(\frac{a}{W}\right)^2 - 23.17\left(\frac{a}{W}\right)^3 + 24.8\left(\frac{a}{W}\right)^4\right\}$$

and $\frac{a}{W} \leq 0.6$. M=bending moment, W=specimen width, B=specimen thickness, a=crack length.

TESTING CONDITIONS

The two series of tests were carried out.

TABLE 3. Testing Conditions

The value of K_{Ii}	Stress Rsyio	Ridr Time (s)	Hold Time (s)	Frequency (HZ)
$K_{Ii} > K_{ISCC}$ K_{Ii} = 38.6 K_{ISCC} = 36.4 ($MPam^{1/2}$)	0.16	4.5 (8)	0	1.11×10^{-1}
			11.0	5.00×10^{-2}
			40.2	2.00×10^{-2}
			77.4	1.15×10^{-2}
			186.0	5.13×10^{-3}
		9.75	0	5.13×10^{-2}
			11.0	3.28×10^{-2}
			40.2	1.68×10^{-2}
			77.4	1.03×10^{-2}
			186.0	4.87×10^{-3}
		15.0 (8)	0	3.33×10^{-2}
			11.0	$2,44\times10^{-2}$
			40.2	1.42×10^{-2}
			186.0	4.63×10^{-3}
$K_{Ii} < K_{ISCC}$ K_{Ii} = 19.9 ($MPam^{1/2}$)	0.31	0.81 (7)	0	6.17×10^{-1}
			1.8	2.92×10^{-1}
			11.0	7.92×10^{-2}
			40.2	2.39×10^{-2}
		4.5	0	1.11×10^{-1}
			1.8	9.26×10^{-2}
			11.0	5.00×10^{-2}
			40.2	2.03×10^{-2}

That is, one series is for the condition that the value of K_{max} of the initial stress intensity factor at starting stage of the crack propagation, K_{Ii} is above K_{Iscc}, that is, $K_{max} > K_{Iscc}$ throughout the crack propagation. Another series is for the condition that the value of K_{Ii} is less than K_{Iscc} and K_{max} increases from below the value of K_{Iscc} and then becomes larger than K_{Iscc} as the crack extends. For each series of the tests, t_R and t_H are changed respectively as shown in TABLE 3. In the present article, stress decreasing time t_D was kept equal to t_R, as it is reported[1)-3)] that the effect of stress decreasing rate is smaller as compared with that of stress increasing rate. The range of $t_H = 0\sim\infty$, and the range of t_R is from 0.81 sec to 15.0 sec, respectivery. The stress ratio $R=\sigma_{min}/\sigma_{max}$ was shown in TABLE 3, where σ_{max}=maximum stress in cycle, and σ_{min}=minimum stress in cycle.

EXPERIMENTAL RESULTS, ANALYSIS AND DISCUSSION

EFFECTS OF STRESS RISE TIME t_R AND STRESS HOLD TIME t_H ON CRACK PROPAGATION RATE UNDER THE CONDITION OF $K_{Ii} > K_{Iscc}$.——Fig.

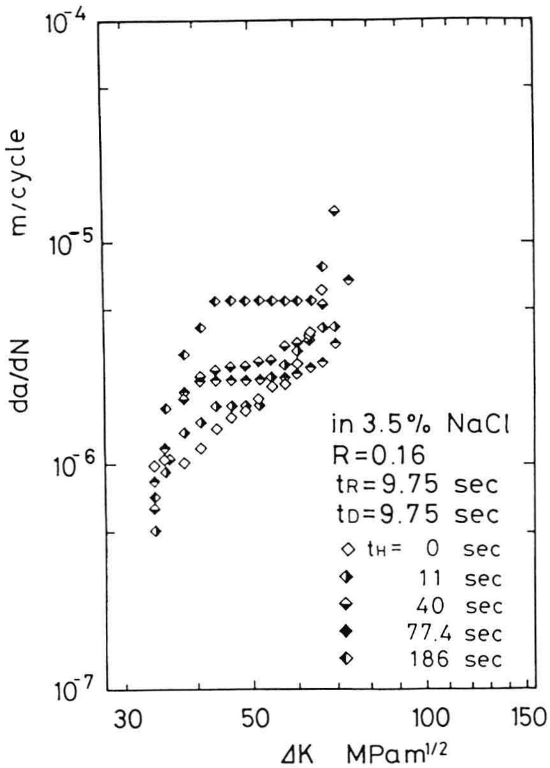

Fig. 3. da/dN versus ΔK with t_H =0~186 sec and t_H=9.75 sec. $K_{Ii} > K_{Iscc}$.

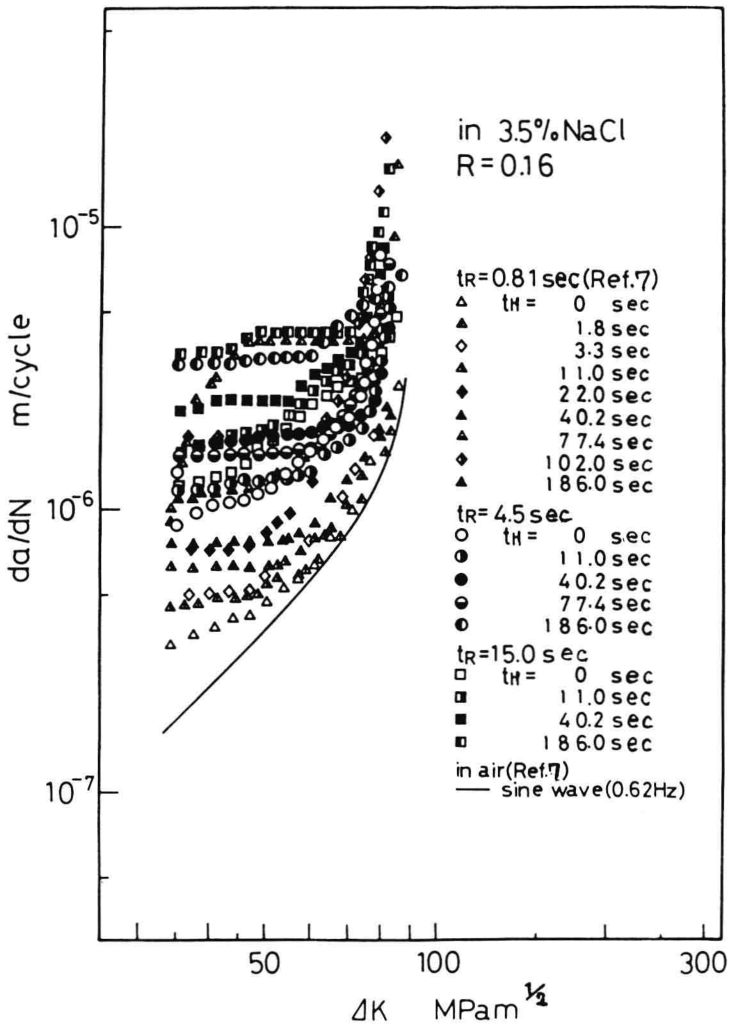

Fig. 4. da/dN versus ΔK with parameters, t_H= 0~186 sec and t_R=0.81~15.0 sec. $K_{Ii} > K_{Iscc}$.

3 shows the effect of stress hold time t_H on the plot of the logarithm of crack propagation rate per cycle, da/dN against the logarithm of stress range intensity factor ΔK for stress rise time t_R=9.75 sec, as an example. With respect to the results of other series of tests, in Fig. 4 log da/dN is plotted against log ΔK with both t_H and t_R as parameters. From Figs. 3 and 4, it can be seen that da/dN and the width of the plateau of da/dN independent of ΔK, increase with increase of t_H. From Figs. 3 and 4, it can be seen that t_H at which the plateau appears becomes shorter with decrease of t_R, and da/dN becomes nearly independent of t_R when t_H is longer. Fig. 4 also shows that the effect of t_R is large when t_H is short.

In Fig. 5 the value of log da/dN at ΔK=46 MPa $m^{\frac{1}{2}}$ in the plateau of log da/dN versus log ΔK diagram as shown in Figs. 3 and 4 was plotted against stress frequency f as changed by t_R and t_H, where f is denoted as follows:

$$f = \frac{1}{2t_R + t_H} \quad . \tag{2}$$

Each solid line in Fig. 5 corresponds to the case where t_R is changed with t_H kept constant, and each dashed line corresponds to the case where t_H is changed with t_R kept constant. For t_H=0, the plateau does not appear. The value of $(da/dN)_{scc}=(1/f)(da/dt)_{plat}$ is shown by dash-dot line in Fig. 5 as the crack growth rate in the stress corrosion cracking where $(da/dt)_{plat}$ is the crack growth rate at the plateau in log (da/dt) versus log ΔK diagram.

With respect to the effect of t_R for specific value of t_H, da/dN shows considerably time dependent behaviour, increasing with

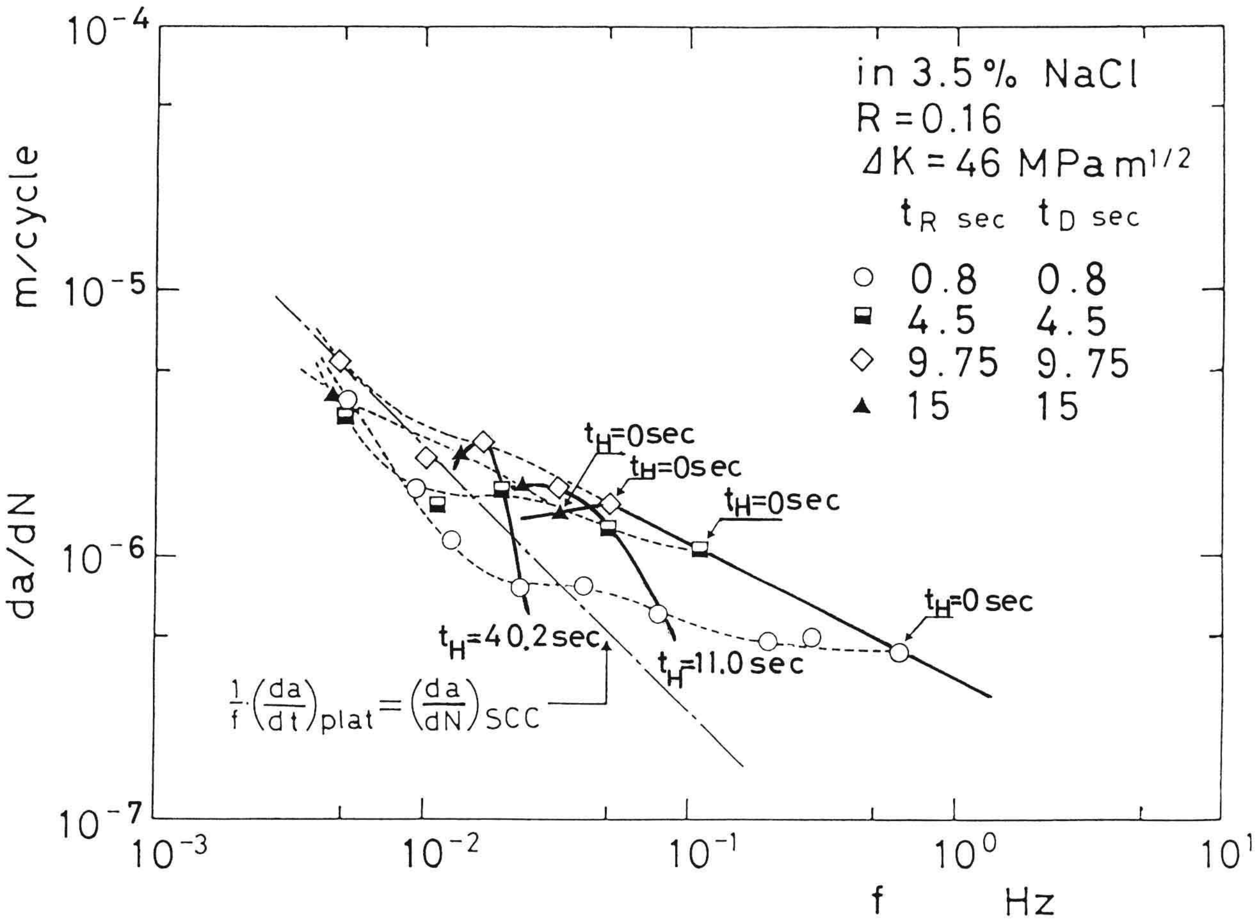

Fig. 5. The relation between da/aN and frequency f as affected by t_H and t_R. $K_{Ii} > K_{Iscc}$.

increase of t_R. With further increase of t_R, da/dN reaches the maximum, say, at t_R=9.75 sec and then tends to decrease. This characteristics may correspond to unstable equilibrium process due to the balance between the accelerating effect by anodic dissolution and deceleration effect by the formation of a non-conductive surface film as t_R increased.[2)]

On the other hand, with respect to the effect of t_H for specific value of t_R, in the range of shorter t_H, that is, in higher frequency region, da/dN is not so much affected by t_H or frequency, although it increases slightly with increase of t_H. From this characteristics it is inferred that da/dN is not only time dependent, but also strongly cycle dependent. However, when t_H increases furthermore, then da/dN accelerates remarkably, and t_R does not affect da/dN so much for this region. That is, da/dN approaches to have only time dependent characteristics.

From the results and the analysis, it can be concluded that time effect by stress wave in higher frequency range is not governed by overall effect, that is, time integral of the stress wave per cycle. The stress wave shape per cycle consists of the two different stages* in series, that is, stress rising stage and the subsequent stage under constant stress. However, t_R has the both time effect as cyclic effect, that is, as included in time gradient of the value of stress during stress rising stage and also the time effect due to a different effect at this stage. On the other hand, t_H has only the time effect due to the different effect pertaining to the latter effect of t_R stage.

EFFECTS OF STRESS RISE TIME t_R AND STRESS HOLD TIME t_H ON CRACK PROPAGATION RATE UNDER THE CONDITION OF $K_{Ii} < K_{Iscc}$.—Fig. 6 shows the results of the effect of stress hold time t_H on the plot of the logarithm of da/dN against the logarithm of stress range intensity factor ΔK for stress rise time t_R=0.81 and 4.5 sec,

* Stress decreasing stage may also concern time effect, but in the present paper it was not discussed as described in the section: TESTING CONDITIONS.

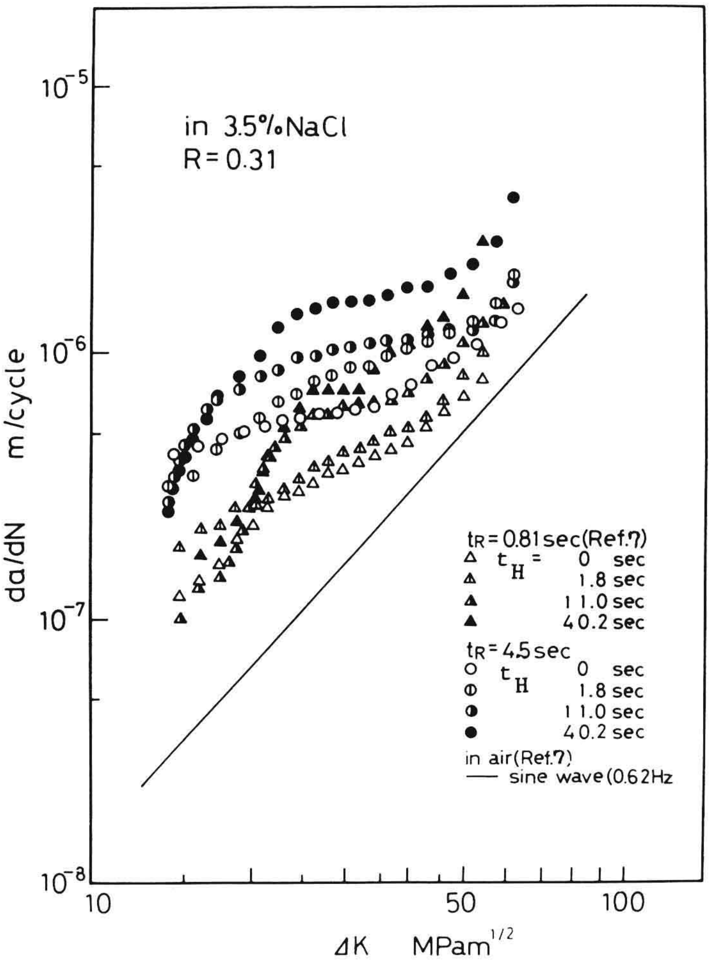

Fig. 6. da/dN versus ΔK with parameters, t_H= 0~40.2 sec and t_R=0.81 and 4.5 sec, respectively. $K_{Ii} < K_{Iscc}$.

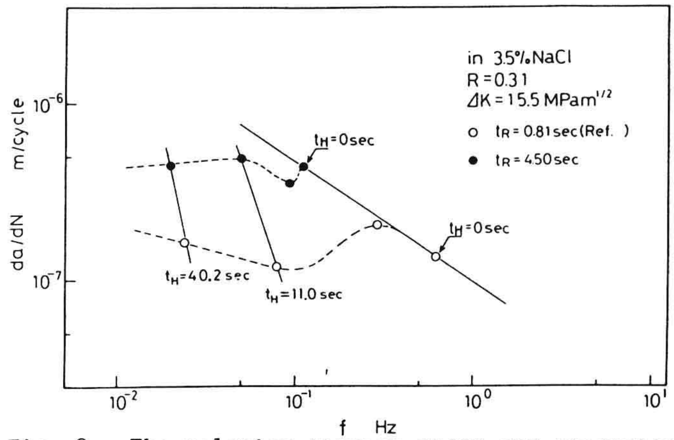

Fig. 8. The relation between da/dN and frequency f as affected by t_H and t_R. $K_{Ii} < K_{Iscc}$.

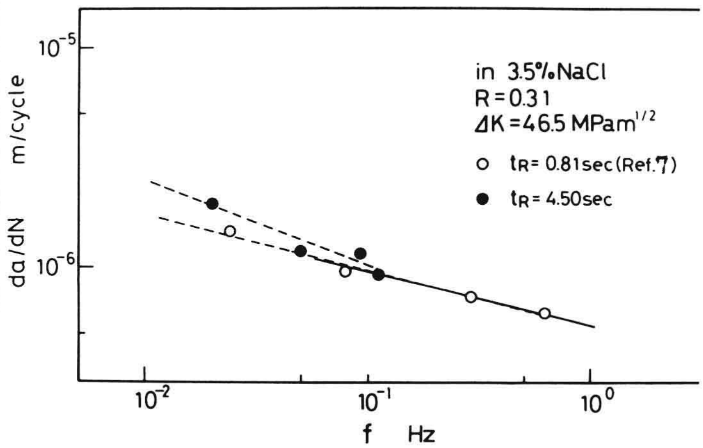

Fig. 9. The relation between da/dN and frequency f as affected by t_H and t_R. $K_{Ii} < K_{Iscc}$.

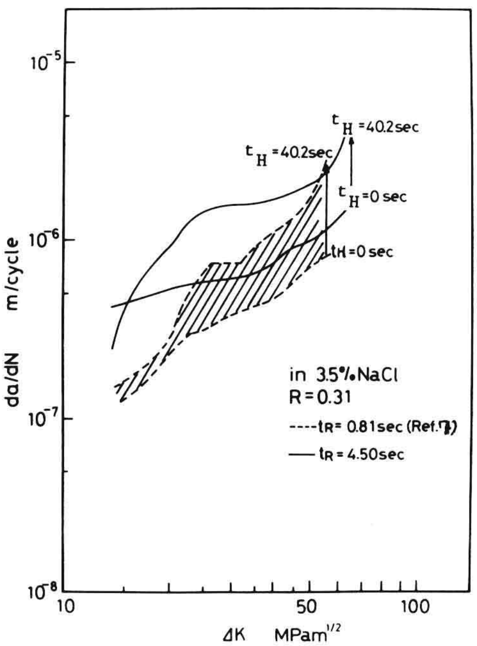

Fig. 7. Illustration of Fig. 6 in terms of band.

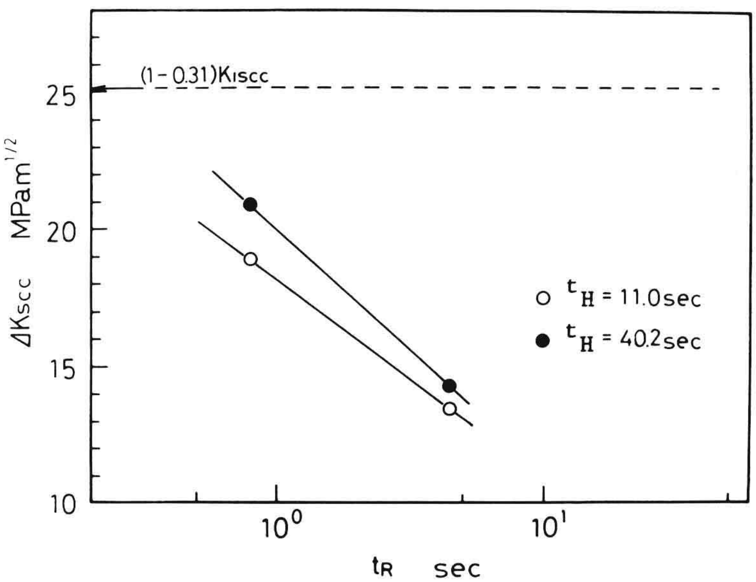

Fig. 10(a). ΔK_{scc} versus t_R.