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STATISTICAL ANALYSES OF VARIABILITY/REPRODUCIBILITY OF ENVIRONMENTALLY ASSISTED CYCLIC CRACK GROWTH RATE DATA UTILIZING JAERI MATERIAL PERFORMANCE DATABASE (JMPD)

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Statistical analyses were conducted by using the cyclic crack growth rate data for pressure vessel steels stored in the JAERI Material Performance Database (JMPD), and comparisons were made on variability and/or reproducibility of the data between obtained by ΔK-increasing and by ΔK-constant type tests. Based on the results of the statistical analyses, it was concluded that ΔK-constant type tests are generally superior to the commonly used ΔK-increasing type ones from the viewpoint of variability and/or reproducibility of the data. Such a tendency was more pronounced in the tests conducted in simulated LWR primary coolants than those in air.

Keywords: Material Performance Database, Pressure Vessel Steel, Fatigue, Cyclic Crack Growth Rate, Statistical Analysis, Stress Intensity Factor Range, Variability, Reproducibility, LWR Primary Coolant

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* on leave from Nuclear Energy Data Center

原子力材料総合データベースＪＭＰＤを利用した環境加速型疲労き裂成長速度データのばらつき／再現性についての統計解析

日本原子力研究所東海研究所燃料・材料工学部
辻　宏和・横山　憲夫*・中島　甫・近藤　達男

（1993年3月5日受理）

材料応用工学研究室で整備を進めている原子力材料総合データベース(JAERI Material Performance Database；ＪＭＰＤ)に格納されている原子炉圧力容器鋼の疲労き裂成長速度データの統計解析を行い，ΔＫ（応力拡大係数範囲）増加型の疲労き裂成長試験で得た速度データとΔＫ一定型の疲労き裂成長試験で得た速度データのばらつき，再現性を比較した。

その結果，データのばらつき，再現性といった観点からは，ΔＫ一定型の疲労き裂成長試験の方が好ましいこと，またその傾向は，大気中のデータよりも軽水炉一次冷却水近似環境中のデータにおいて，より顕著であることが分かった。

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Contents

目　　次

1. Introduction

Cyclic crack growth rate data for pressure vessel steels have been accumulated mainly through the activity of the International Co-operative Group on Cyclic Crack Growth Rate (the ICCGR Group) [1-3] in relation to defect evaluation of nuclear power plant components. The data have been stored in the JAERI Material Performance Database (JMPD)[4]. Most of them were obtained by the common constant-load-amplitude (ASTM E647 [5] based) tests, i.e., ΔK (stress intensity factor range) -increasing type tests, while those by ΔK-constant type are less common.

Generally speaking, in order to examine the dependence of some phenomenon on some parameter, the parameter is desired to be kept constant and independent of the resultant phenomenon or change of property to be measured. In the case of cyclic crack growth tests, the parameter which should be kept constant, i.e., an independent variable, is the ΔK and the value to be measured, i.e., the subject variable, is the da/dN (cyclic crack growth rate).

Regarding the known large population of influential factors and the sequential effects of those, any difference that might result in variability and/or reproducibility of crack growth rate measurement can be made clear by comparison between ΔK-increasing and ΔK-constant type tests. In fact an appreciable difference between those was observed already by the authors through the fatigue crack growth tests for a low alloy steel SA533B-1 in air [6]. The trend has been suspected to become more apparent when the tests are conducted in corrosive environments where more variables, hence uncertainties, are included during the tests. From such a viewpoint, statistical analyses were conducted by using some typical data sets stored in the JMPD in the present work.

2. Experimental observation in air environment tests [6]

Fatigue crack growth tests on SA533B-1 steel were conducted in air with both the compact-tension (CT) and the contoured-double-cantilever-beam (CDCB) specimens for comparison, which corresponded to ΔK-increasing and ΔK-constant type tests, respectively. The tests were conducted with ten CT and six CDCB specimens at a frequency of 0.5 Hz.

Figures 1(a) and 1(b) show da/dN versus ΔK relations for each data set. As can be seen in those figures, the data by ΔK-increasing type tests scatter more widely than those by ΔK-constant type.

Correlation coefficients for the da/dN versus ΔK relations, standard deviations about the regression lines and standard deviations about the mean da/dN in the obtained data were evaluated. The results have revealed that correlation coefficients for the data obtained by ΔK-constant type tests are always larger than those for the data by ΔK-increasing type (see Fig. 2), standard deviations about the regression lines for the data obtained by ΔK-constant type tests are obviously smaller than those by ΔK-increasing type (see Fig. 3), and standard deviations about the mean da/dN at any ΔK level for the data obtained by ΔK-constant type tests are smaller than those by ΔK-increasing type (see Fig. 4). It has been also pointed out that standard deviations about the mean da/dN are larger at low and high ΔK levels than those at intermediate ΔK levels in ΔK-increasing type tests as can be seen in Fig. 4.

3. Data for statistical analyses

In an attempt, all the data of cyclic crack growth rate on low alloy steels stored in the JMPD, where not only the data in Ref.[6] but also the data obtained by the authors and by many other investigators [1-3] were stored, were classified into 14 categories based on materials and test environments as shown in Table 1. The materials were SA533B-1

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In the present work the data of five categories shown in Table 1 were eventually analyzed. In addition to the da/dN versus ΔK relations, the corresponding versions of the effective stress intensity factor range were also examined. The effective stress intensity factor range, ΔKe, used in the present study is defined as follows [8];

$$\Delta Ke = \frac{\Delta K}{2.88 - R}, \qquad (1)$$

where R is Kmin/Kmax.

Statistical analyses were conducted separately for the data obtained by ΔK-increasing and by ΔK-constant type tests. Figures 5(a) and 5(b) show a comparison based on the data obtained in air environment. Figures 6 through 9 show da/dN versus ΔK relations for each data set obtained in aqueous environments for different material-environmental combination. Figures 10 through 14 show the sets of ΔKe versions for air and aqueous environments. The data set identification and the number of the data sets analyzed are shown in Tables 2 and 3, respectively.

4. Evaluation of statistically analyzed results

4.1 Correlation coefficient

Correlation coefficients for da/dN versus ΔK and/or da/dN versus ΔKe relations were calculated as follows.

$$r = \frac{1}{N} \sum_{i} \frac{([\log_{10}\Delta K]_i - \overline{\log_{10}\Delta K})\ ([\log_{10}da/dN]_i - \overline{\log_{10}da/dN})}{S_x\ S_y} \tag{2}$$

for da/dN versus ΔK relations,

and

$$r = \frac{1}{N} \sum_{i} \frac{([\log_{10}\Delta Ke]_i - \overline{\log_{10}\Delta Ke})\ ([\log_{10}da/dN]_i - \overline{\log_{10}da/dN})}{S_x\ S_y} \tag{3}$$

for da/dN versus ΔKe relations,

where r, N, S_x and S_y are the correlation coefficient, the number of the samples, standard deviations of $\log_{10}\Delta K$ and $\log_{10}da/dN$, respectively.

The results are shown in Fig. 15. It can be seen that correlation coefficients for the data obtained by ΔK-constant type tests are always larger than those for by ΔK-increasing type. It is clear that the correlation coefficients for the data in air are generally larger than those in simulated LWR primary coolants. The difference in correlation coefficients between both types of tests is more pronounced for the data in the aqueous environments. It is also pointed out that correlation coefficients for the plot using ΔKe are only slightly raised.

It can be tested whether the difference in correlation coefficients is significant or not by using the following technique [9].

If $r \neq 0$, the values of Z-transformation from r approximately exhibit the normal distribution. Z-transformation is defined as follows;

$$Z = \frac{1}{2} \log_e \frac{1 + r}{1 - r}\ . \tag{4}$$

As the values of Z-transformation from r approximately exhibit the normal distribution, it is possible to examine whether the difference in correlation coefficients is significant or not by comparison of the value of Y with that of the standard normal distribution table. The value of Y is determined as follows;

$$Y = \frac{|Z_1 - Z_2|}{\sqrt{\dfrac{1}{N_1 - 3} + \dfrac{1}{N_2 - 3}}}, \tag{5}$$

where N is the number of samples. Since the number of samples is taken in the determination of the value of Y, this technique can cope with the case where the difference in the number of samples between the compared data sets is rather large.

The results of the above-mentioned statistical test are summarized in Table 4. The difference in correlation coefficients for the data between by ΔK-increasing and by ΔK-constant type tests is significant with a level of 5 % in all the cases analyzed in the present work. The difference in correlation coefficients for the data between in-air and in-water is also significant with a level of 5 %. On the other hand, it can be hypothesized in many cases with a level of 5 % that there is essentially no significant difference in the correlation coefficients between the contexts of using ΔK and ΔKe.

4.2 Standard deviation about regression line

The regression lines for each data set were calculated by means of the following model,

$$da/dN = C\ \Delta K^n \quad \text{for } da/dN \text{ versus } \Delta K \text{ relations,} \tag{6}$$

and

$$da/dN = C\ \Delta Ke^n \quad \text{for } da/dN \text{ versus } \Delta Ke \text{ relations,} \tag{7}$$

where C and n are constants. Table 5 presents the regression parameters C and n determined for each data set where da/dN, ΔK and/or ΔKe are expressed in mm/cycle and in $MPa\sqrt{m}$, respectively.

Standard deviations about the above-mentioned regression lines were evaluated. The results are shown in Fig. 16. Standard deviations about the regression lines for the data by ΔK-constant type tests are smaller than those by ΔK-increasing type, with one exceptional case of the data set No. 5, i.e., the data set for SA533B-1 with high sulfur in boiling water reactor (BWR) environment. As shown in Fig. 9(a), the data are concentrated only at a limited ΔK region in this particular case. Such a fact may have caused a part of the uniqueness of the result, but further attention should be paid in future studies.

As can be seen in Fig. 16, standard deviations about the regression lines for the data in air are smaller than those in water, and the difference in those between both types of tests is clearer for the data in water than in air. It is also pointed out that standard deviations about the regression lines for da/dN versus ΔKe relations are only slightly smaller than the ΔK regime.

4.3 Standard deviation about mean da/dN

Standard deviations about the mean da/dN were evaluated at several different ΔK levels. Only one pair of plot for each specimen was used at a specific ΔK and/or ΔKe level. Although the method may have some limitation as suggested by Clark, Jr. et al. [10], it is believed to be beneficial in making a comparison of the tendencies in variability and/or reproducibility for the data set. The results of the evaluation are shown in Figs. 17 and 18 for the ΔK and the ΔKe regimes, respectively. In those figures, standard deviations are expressed as the ratios to the mean da/dN.

The tendencies that standard deviations about the mean da/dN at any ΔK level for the data by ΔK-constant type tests are smaller than those by ΔK-increasing type are clearly recognized. Although standard deviations about the mean da/dN for the air data are slightly smaller than those for the water data, the tendency is not so clear. There is no difference in standard deviations between ΔK and ΔKe regimes.

In Figs. 17 and 18, it should be noted that standard deviations about the mean da/dN increase at lower ΔK levels, especially in ΔK-increasing type tests. The trend may be due to the following facts.

table differences like a preimmersion period among the tests are included and they affect the crack growth rate [11] in the earlier stage of the tests, i.e., at lower ΔK region. Secondly, the crack growth rate data are subject to the precision of crack length measurements, and naturally the precision is less when the crack is short. It has been fatally the case that cracks are generally short at lower ΔK region in most constant-load-amplitude, ΔK-increasing type tests. The facts may apply to both types of tests. The effects, however, can easily be suppressed in ΔK-constant type tests since crack length is not affecting the ΔK level, and any low ΔK tests can be made after extending the crack length to an adequate level.

5. Discussion

In the analyses the attention was focused mainly on the accuracy of the experiments. No special attention, however, was paid to possible probabilistic phenomena peculiar to environmentally assisted cracking (EAC) under some particular combination of material, environment and loading conditions. The data sets selected for the analyses in the present work happened to be in the range without frequent occurrence of the EAC effects particularly for ΔK-constant type tests. If the EAC effects such as brittle mode crack growth occur frequently, the wide data scatter band will arise regardless of ΔK control modes.

One of the predominant factors in corrosion fatigue crack growth rate to be taken into consideration is the time-base pure fatigue growth rate, $[da/dt]_{air}$, which is almost equivalent to the crack tip blunting rate or strain rate [12]. This predominant factor is fixed in ΔK-constant type tests. Therefore superiority of ΔK-constant type tests to ΔK-increasing type ones may become more clear in the case where the EAC effects frequently occur. In such a case, one should be able to recognize the deviation due to EAC more clearly in ΔK-constant type tests because of its higher accuracy and reproducibility.

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6. Summary

Statistical analyses were conducted by using the cyclic crack growth rate data for pressure vessel steels stored in the JAERI Material Performance Database (JMPD), and comparisons were made on variability and/or reproducibility of the data between obtained by ΔK-increasing and by ΔK-constant type tests.

Based on the analytical results in the present work, the following conclusions were drawn;

(1) ΔK-constant type tests are generally superior to the commonly used ΔK-increasing type ones from the viewpoint of variability and/or reproducibility of the data.

(2) The differences in variability and/or reproducibility of the data between those two types of tests are more pronounced for the data in simulated LWR primary coolants than those in air.

(3) Variability is larger at lower ΔK levels, especially in the data by ΔK-increasing type tests.

(4) The effective stress intensity factors, which are referred to in the present statistical analyses, cause negligible effect in improving the data plots.

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Table 1 Classification and selection of data sets

Material / Environment	SA533B−1			SA508−2		
	S≦0.005%	0.005%<S≦0.0125%	0.0125%<S	S≦0.005%	0.005%<S≦0.0125%	0.0125%<S
PWR water 280℃≦T≦320℃	B	A	A	B	A	B
BWR water 280℃≦T≦320℃	B	B	A	B	B	B
Air T≦50℃	A			B		

A : Statistically analyzed
B : Enough data are not available for statistical analysis

Table 2 Data set identification

1i	ΔK-increasing	SA533 B-1	Air	da/dN versus ΔK
1c	ΔK-constant			
2i	ΔK-increasing	SA533 B-1 Medium S	PWR water	
2c	ΔK-constant			
3i	ΔK-increasing	SA533 B-1 High S		
3c	ΔK-constant			
4i	ΔK-increasing	SA508-2 Medium S		
4c	ΔK-constant			
5i	ΔK-increasing	SA533 B-1 High S	BWR water	
5c	ΔK-constant			
1ei	ΔK-increasing	SA533 B-1	Air	da/dN versus ΔKe
1ec	ΔK-constant			
2ei	ΔK-increasing	SA533 B-1 Medium S	PWR water	
2ec	ΔK-constant			
3ei	ΔK-increasing	SA533 B-1 High S		
3ec	ΔK-constant			
4ei	ΔK-increasing	SA508-2 Medium S		
4ec	ΔK-constant			
5ei	ΔK-increasing	SA533 B-1 High S	BWR water	
5ec	ΔK-constant			

Table 3 The number of data sets statistically analyzed

Data set No.	The number of specimens	The number of da/dN vs ΔK pairs	Data set No.	The number of da/dN vs ΔK pairs
1i	37	1980	1c	92
2i	68	1135	2c	39
3i	68	1991	3c	94
4i	36	1275	4c	119
5i	21	705	5c	50

Table 4 Results of statistical test

1i vs 1c	A	1i vs 1ei	B	1i vs 4i	A
2i vs 2c	A	2i vs 2ei	B	1ei vs 4ei	A
3i vs 3c	A	3i vs 3ei	B	1c vs 4c	A
4i vs 4c	A	4i vs 4ei	A	1ec vs 4ec	A
5i vs 5c	A	5i vs 5ei	B		
1ei vs 1ec	A	1c vs 1ec	B		
2ei vs 2ec	A	2c vs 2ec	B		
3ei vs 3ec	A	3c vs 3ec	A		
4ei vs 4ec	A	4c vs 4ec	B		
5ei vs 5ec	A	5c vs 5ec	B		

A : Difference is significant with a level of 5 %.

B : Difference is not significant with a level of 5 %.

Table 5 Regression parameters C and n
(da/dN: mm/cycle, $\Delta K, \Delta Ke$: $MPa\sqrt{m}$)

Data set No.	C	n	Data set No.	C	n
1i	1.87×10^{-8}	2.52	1ei	1.67×10^{-7}	2.68
1c	1.05×10^{-9}	3.42	1ec	2.86×10^{-8}	3.47
2i	3.95×10^{-7}	2.15	2ei	1.28×10^{-6}	2.46
2c	2.27×10^{-8}	2.79	2ec	3.45×10^{-7}	2.83
3i	2.88×10^{-6}	1.68	3ei	6.13×10^{-6}	1.99
3c	3.10×10^{-8}	2.71	3ec	1.17×10^{-7}	3.17
4i	2.36×10^{-7}	2.18	4ei	9.39×10^{-7}	2.48
4c	5.14×10^{-8}	2.47	4ec	2.83×10^{-7}	2.67
5i	3.14×10^{-8}	2.89	5ei	4.88×10^{-7}	2.93
5c	3.27×10^{-7}	2.08	5ec	6.96×10^{-7}	2.52

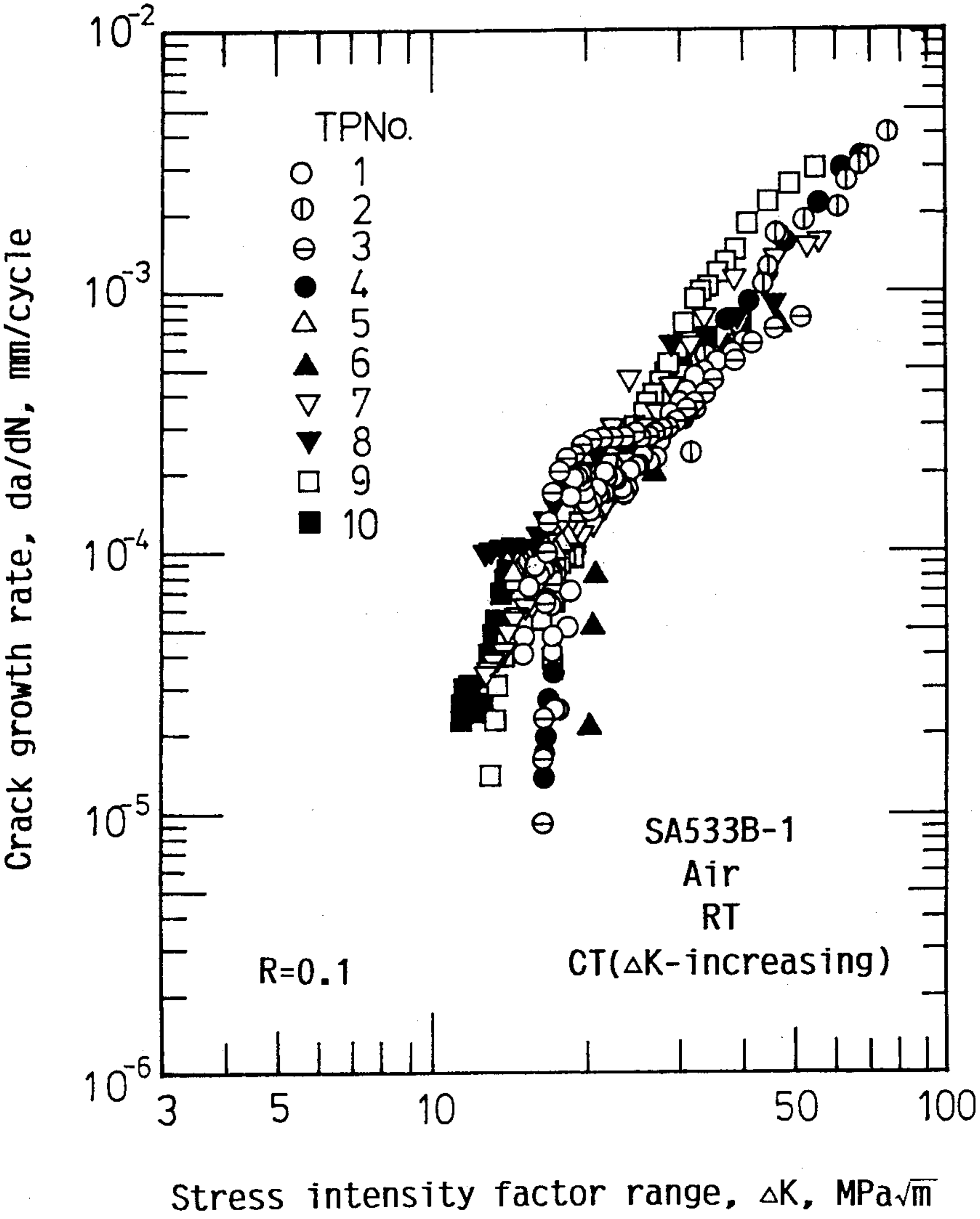

Fig. 1(a) da/dN versus ΔK for SA533B-1 in air with CT specimens by ΔK-increasing type tests [6].

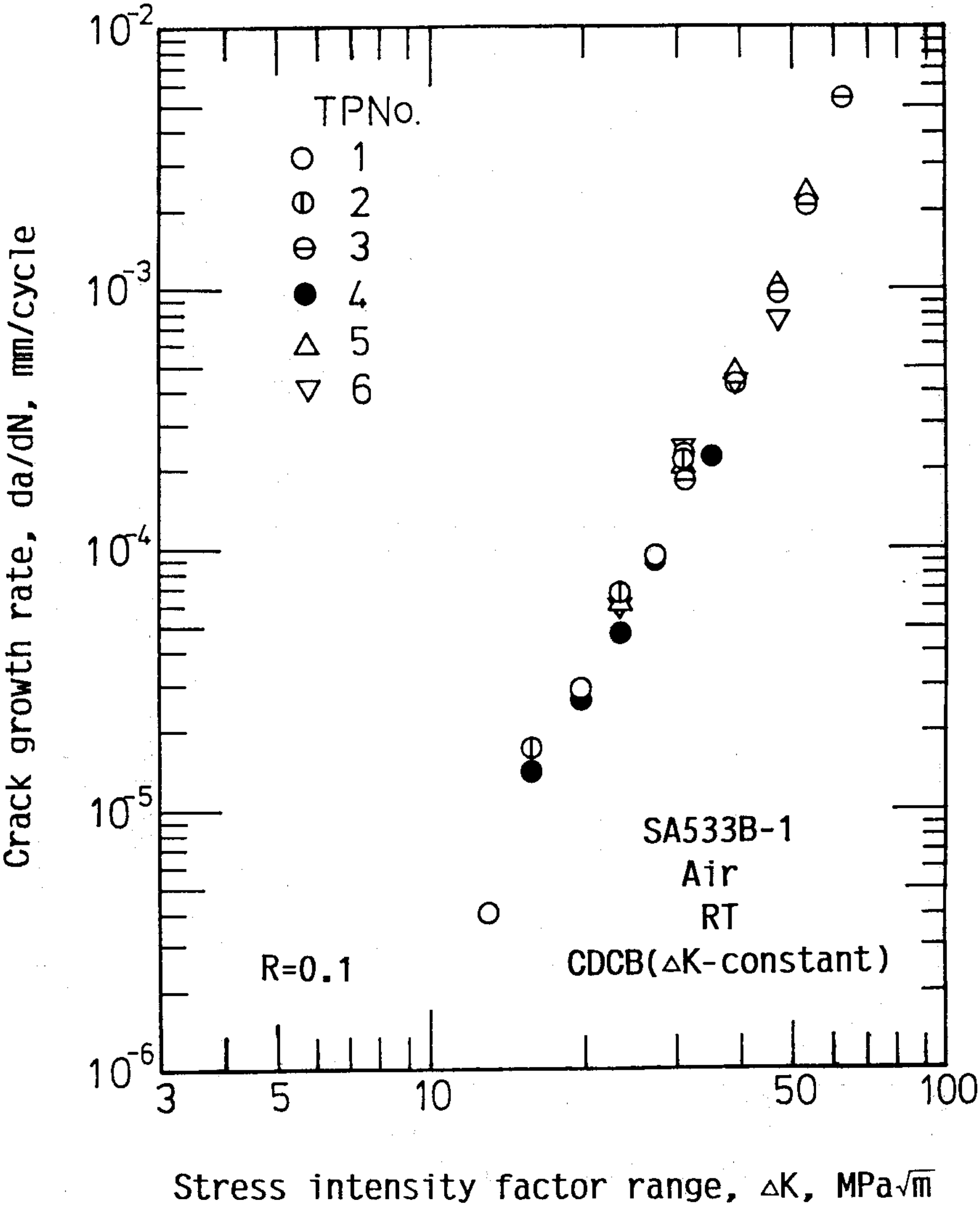

Fig. 1(b) da/dN versus ΔK for SA533B-1 in air with CDCB specimens by ΔK-constant type tests [6].

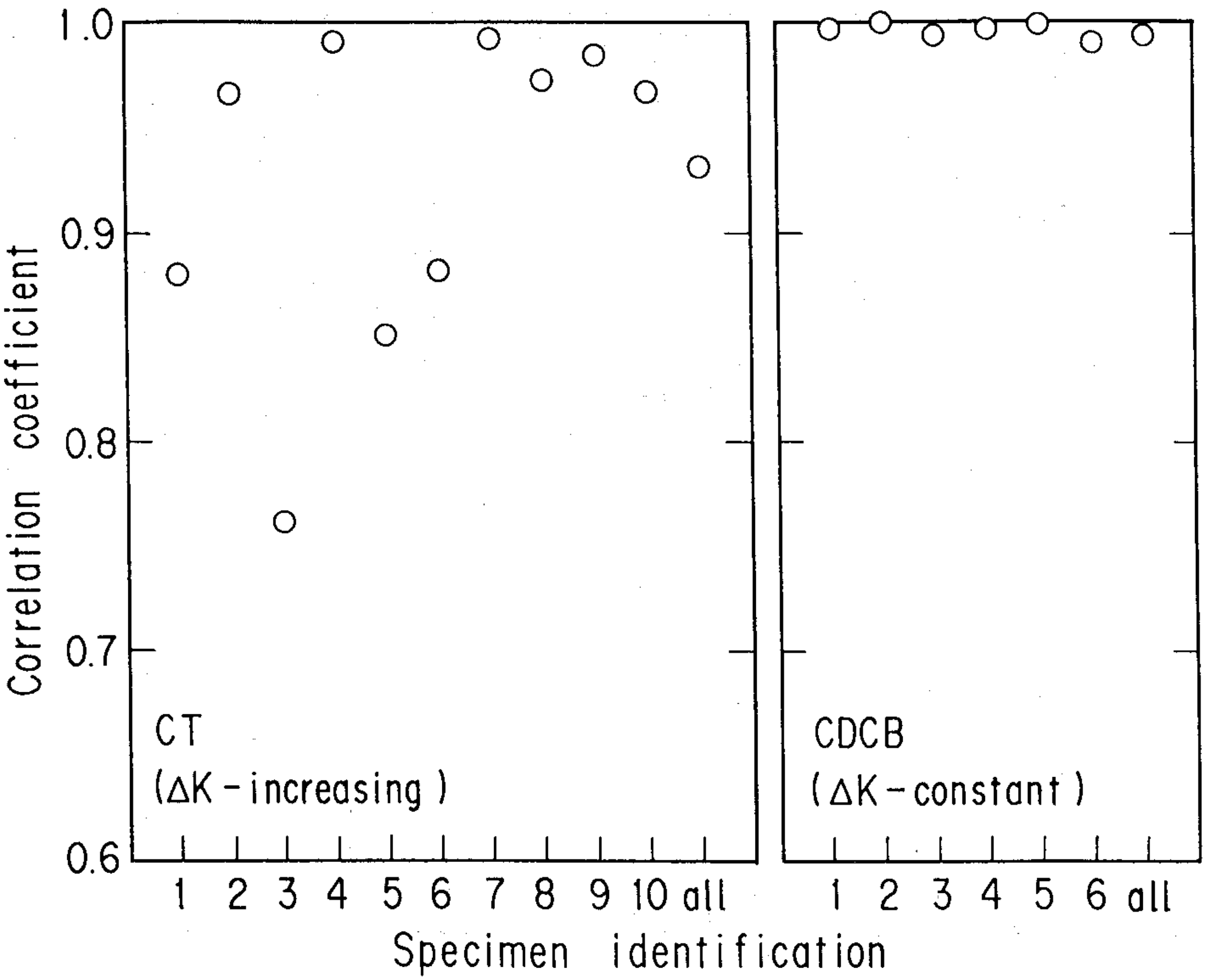

Fig. 2 Correlation coefficients for da/dN versus ΔK relations of SA533B-1 in air [6].

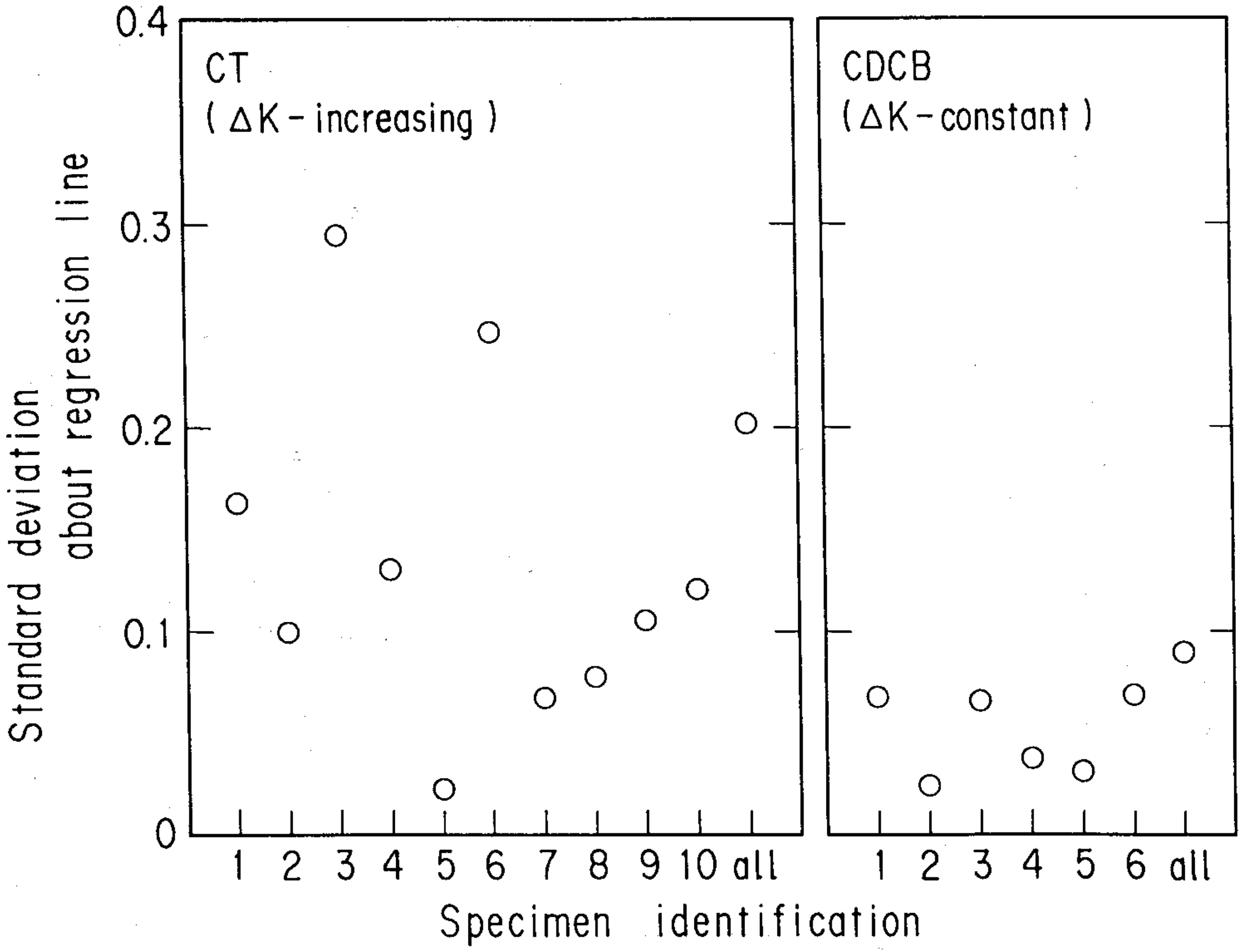

Fig. 3 Standard deviations about regression lines for SA533B-1 in air [6].

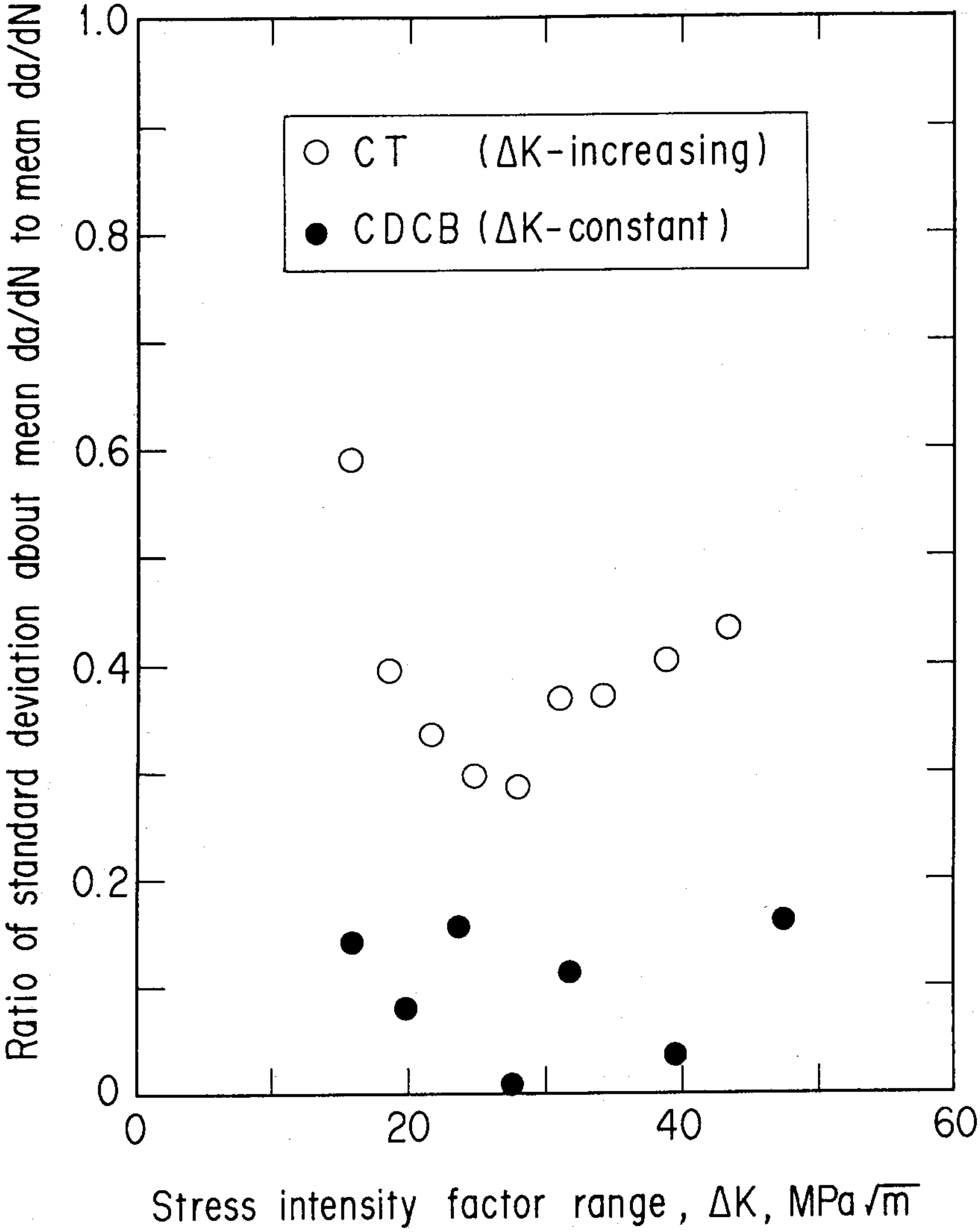

Fig. 4 Standard deviations about mean da/dN at several different ΔK levels for da/dN versus ΔK data on SA533B-1 in air [6].

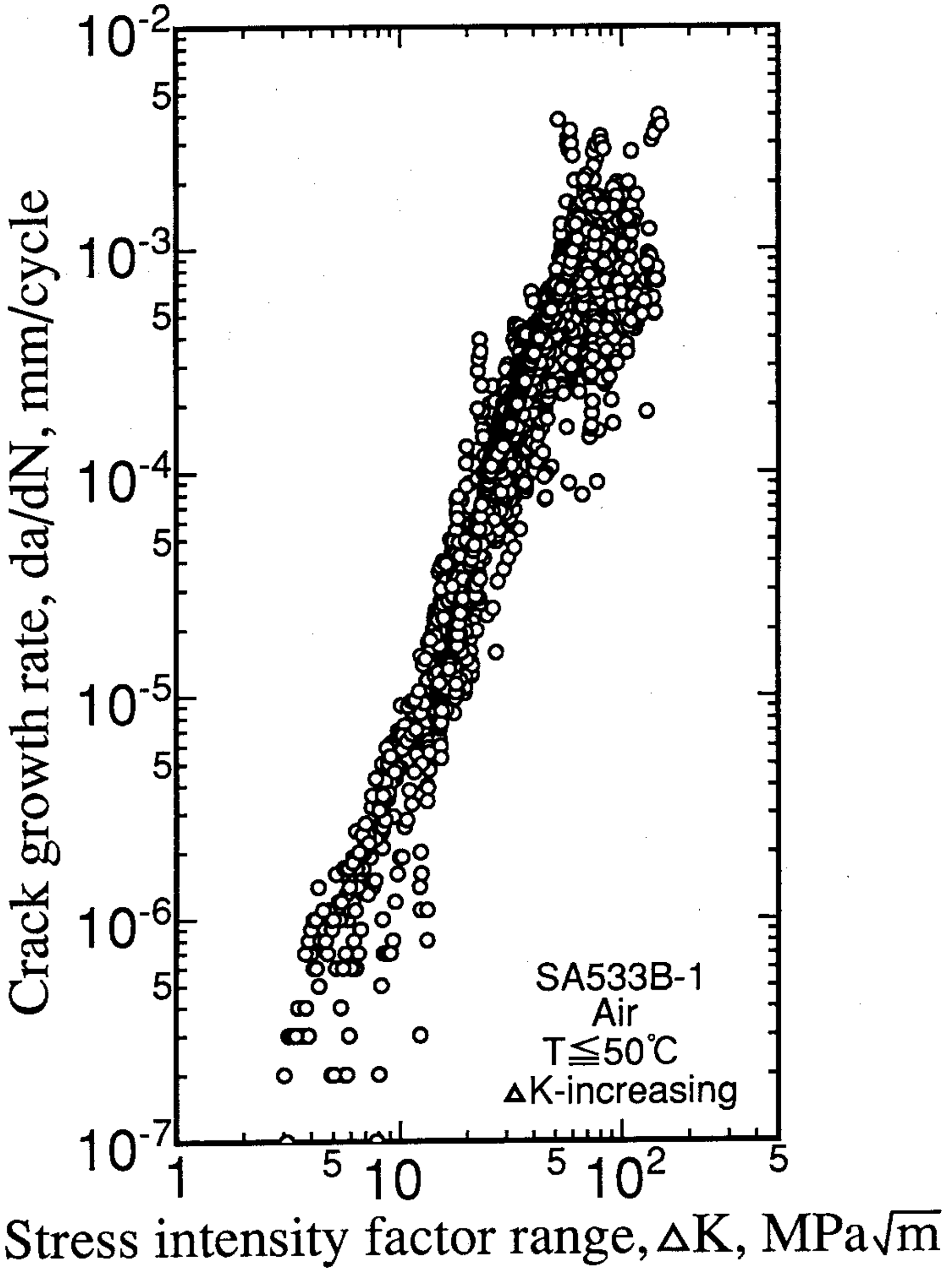

Fig. 5(a) da/dN versus ΔK for SA533B-1 in air by ΔK-increasing type tests. (data set No.1i)

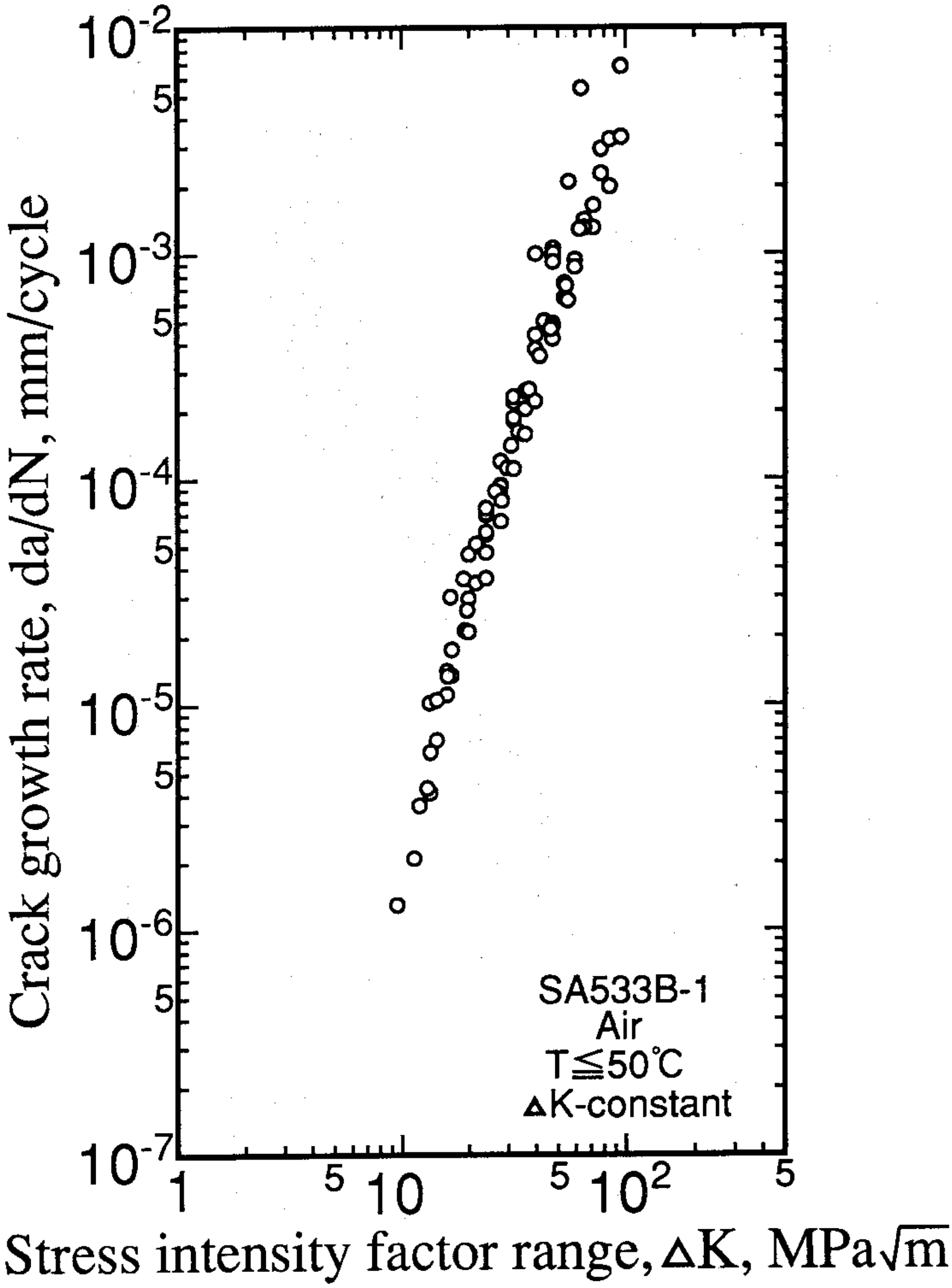

Fig. 5(b) da/dN versus ΔK for SA533B-1 in air by ΔK-constant type tests. (data set No.1c)

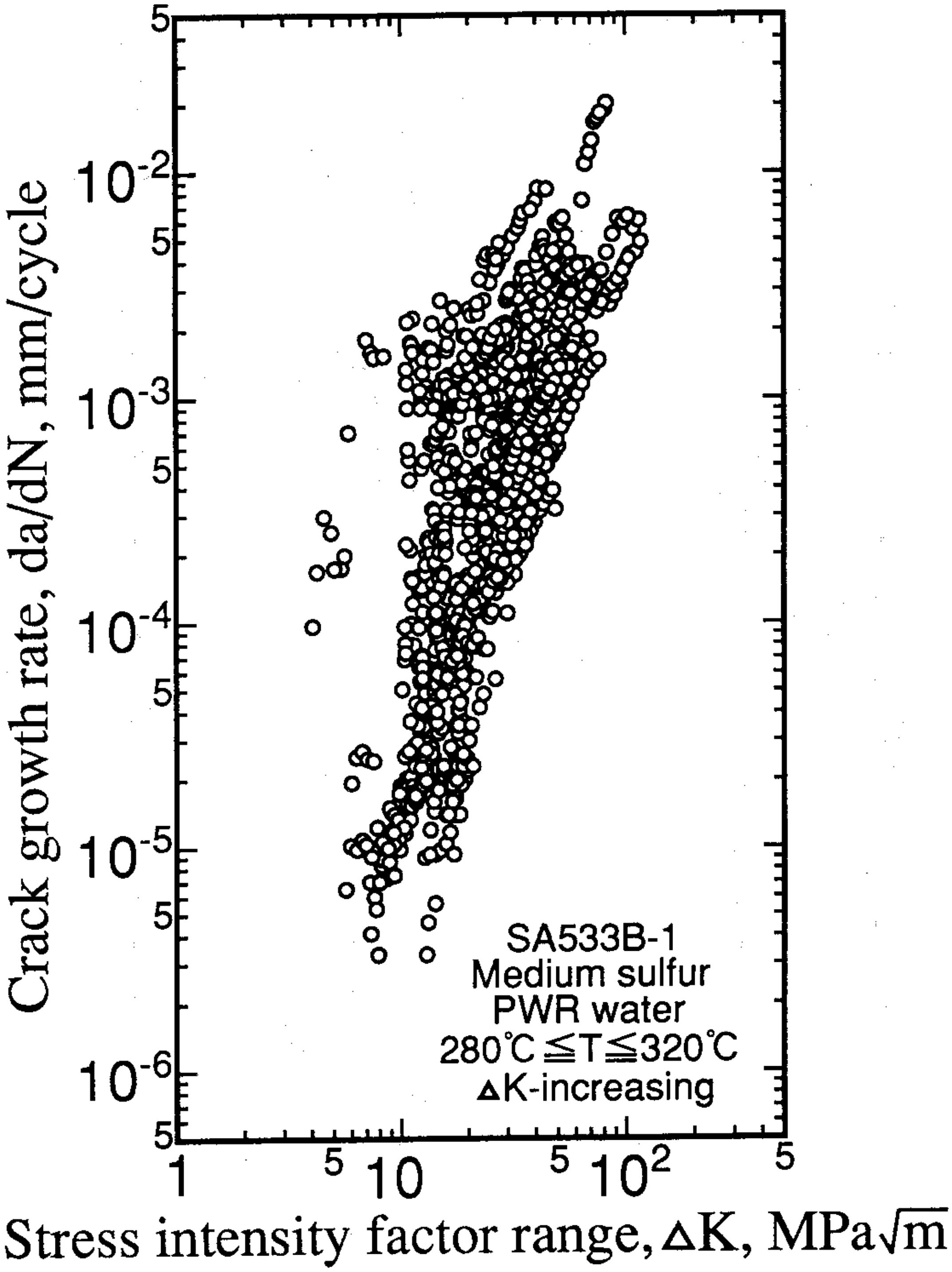

Fig. 6(a) da/dN versus ΔK for SA533B-1 with medium sulfur in PWR type water by ΔK-increasing type tests. (data set No.2i)

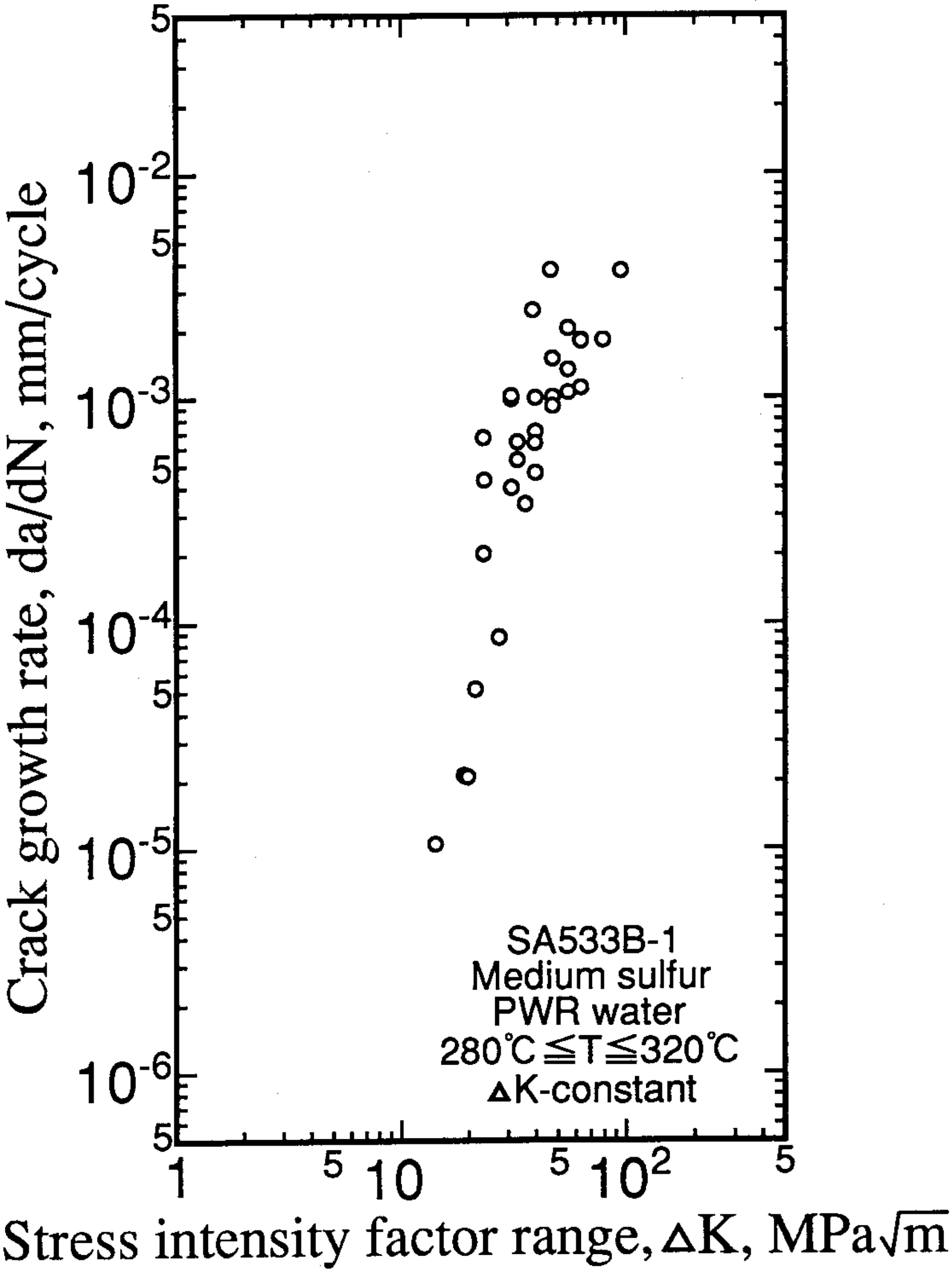

Fig. 6(b) da/dN versus ΔK for SA533B-1 with medium sulfur in PWR type water by ΔK-constant type tests. (data set No.2c)

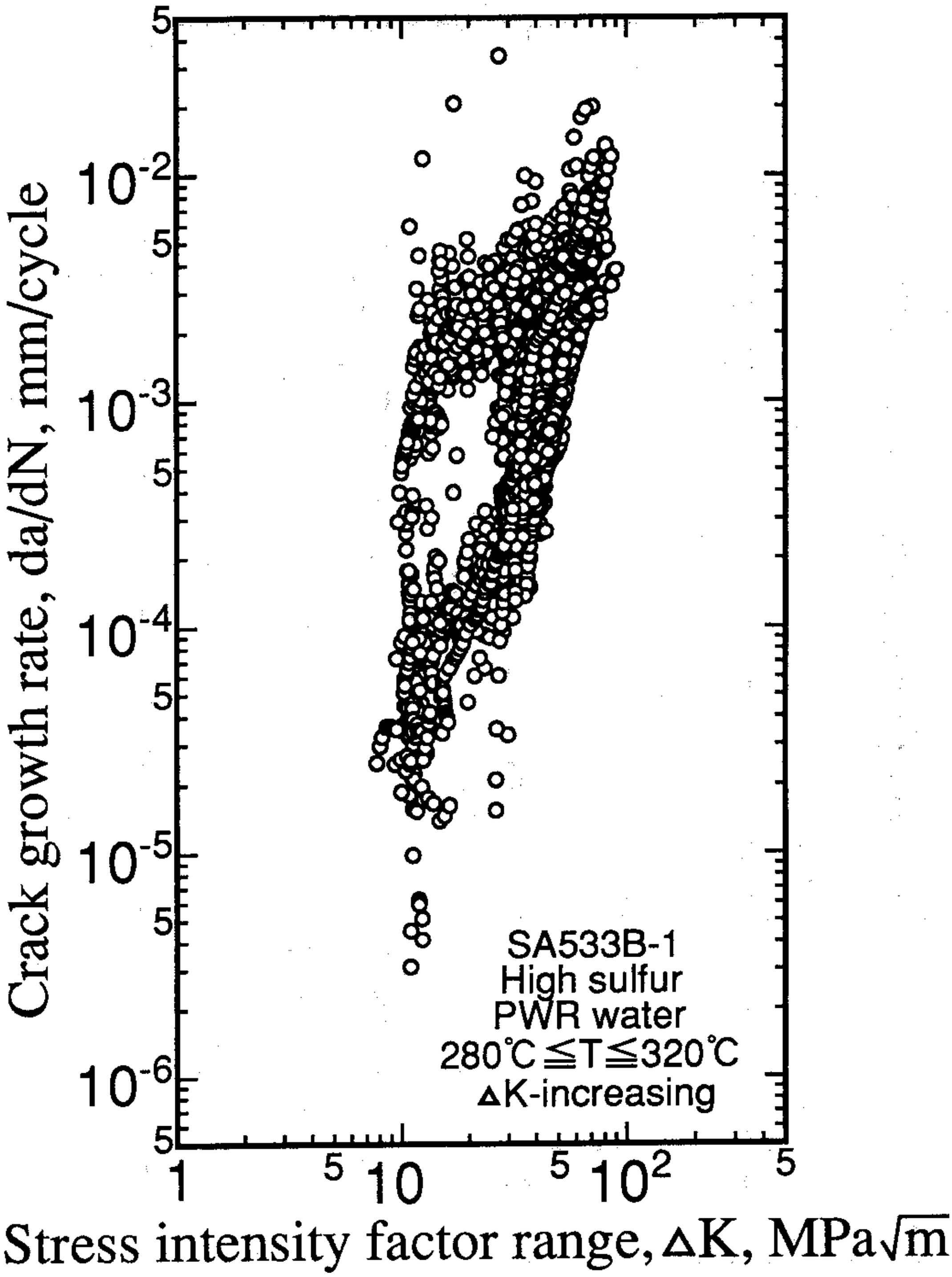

Fig. 7(a) da/dN versus ΔK for SA533B-1 with high sulfur in PWR type water by ΔK-increasing type tests. (data set No.3i)

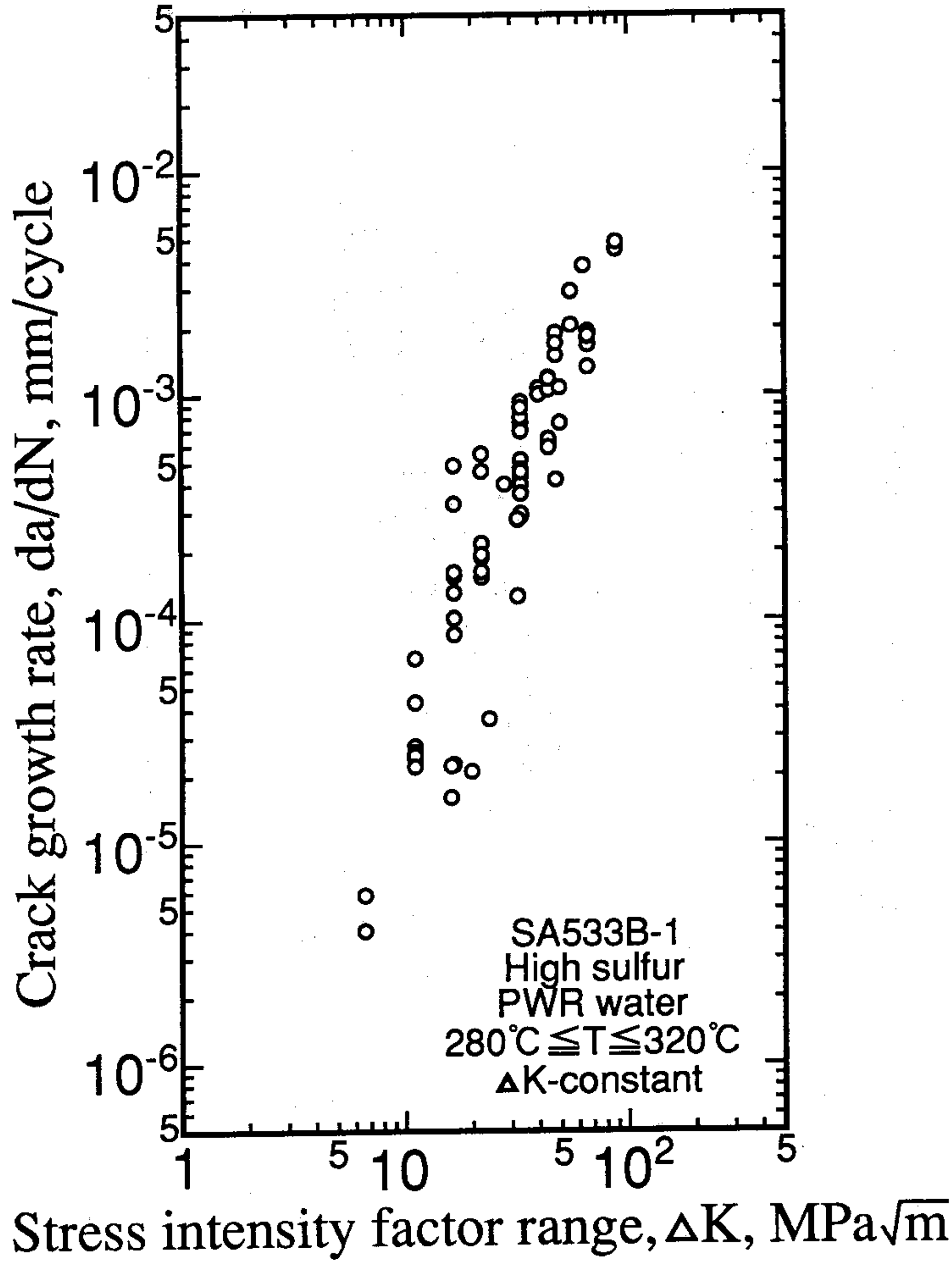

Fig. 7(b) da/dN versus ΔK for SA533B-1 with high sulfur in PWR type water by ΔK-constant type tests. (data set No.3c)

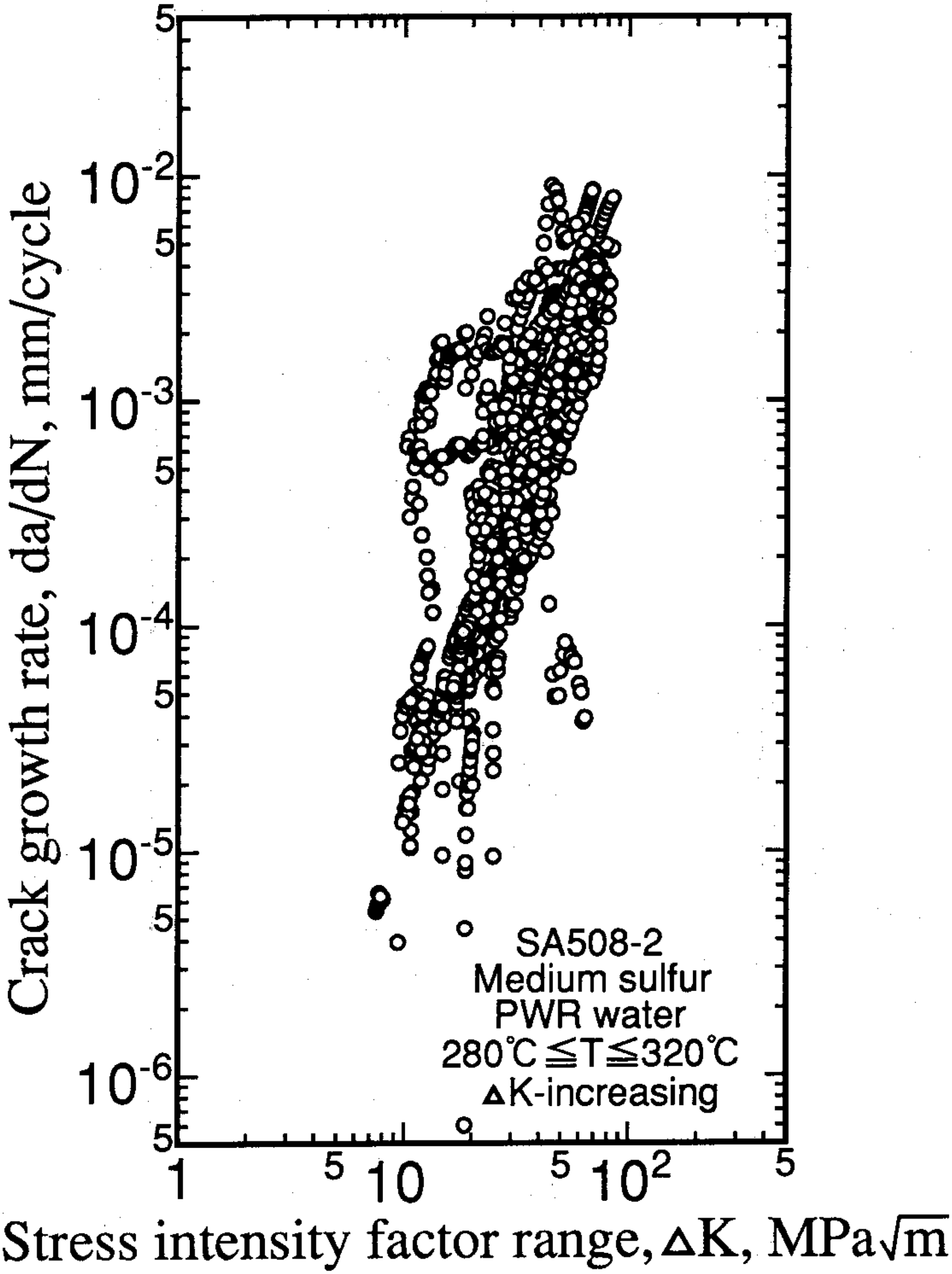

Fig. 8(a) da/dN versus ΔK for SA508-2 with medium sulfur in PWR type water by ΔK-increasing type tests. (data set No.4i)

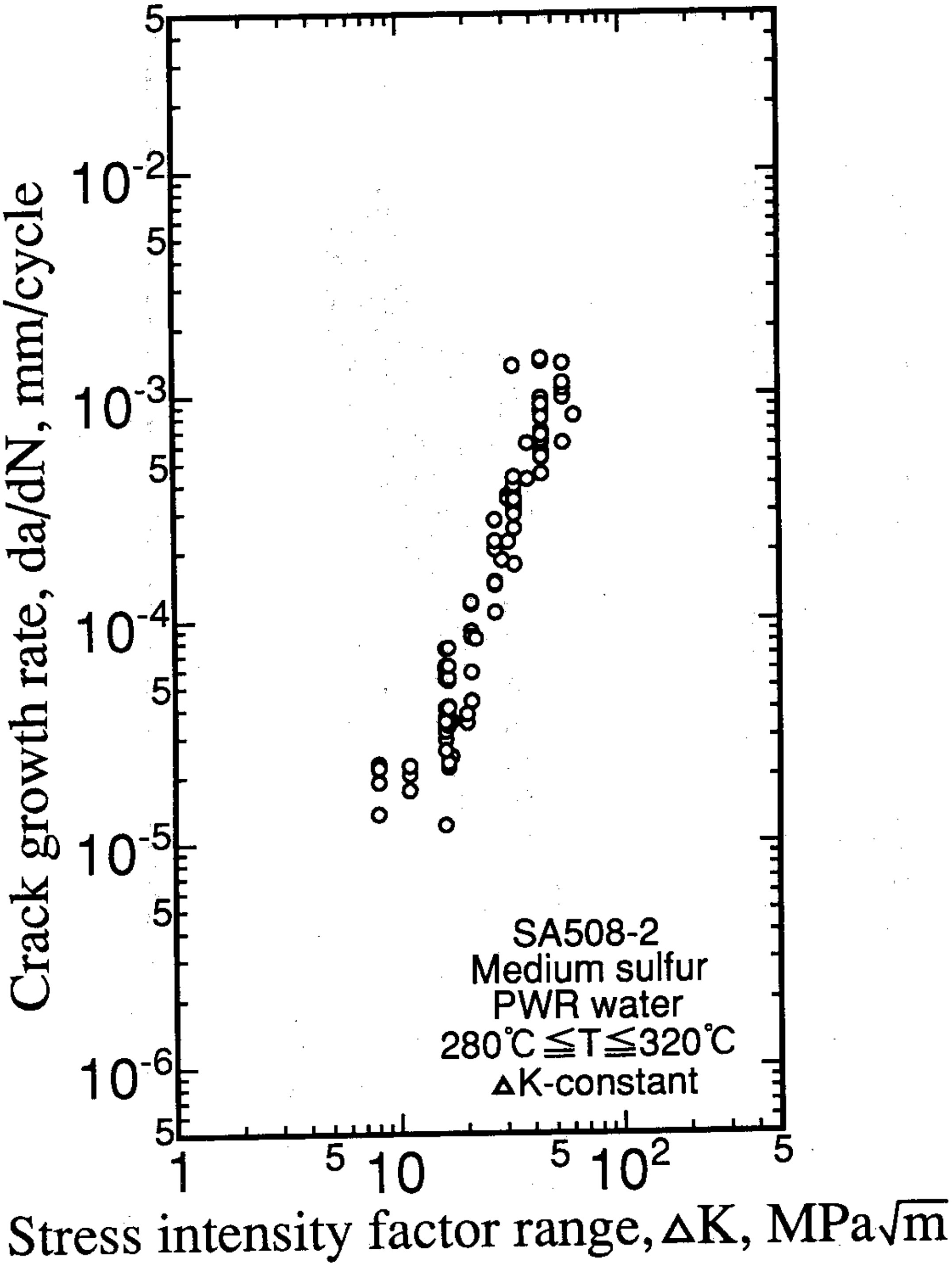

Fig. 8(b) da/dN versus ΔK for SA508-2 with medium sulfur in PWR type water by ΔK-constant type tests. (data set No.4c)

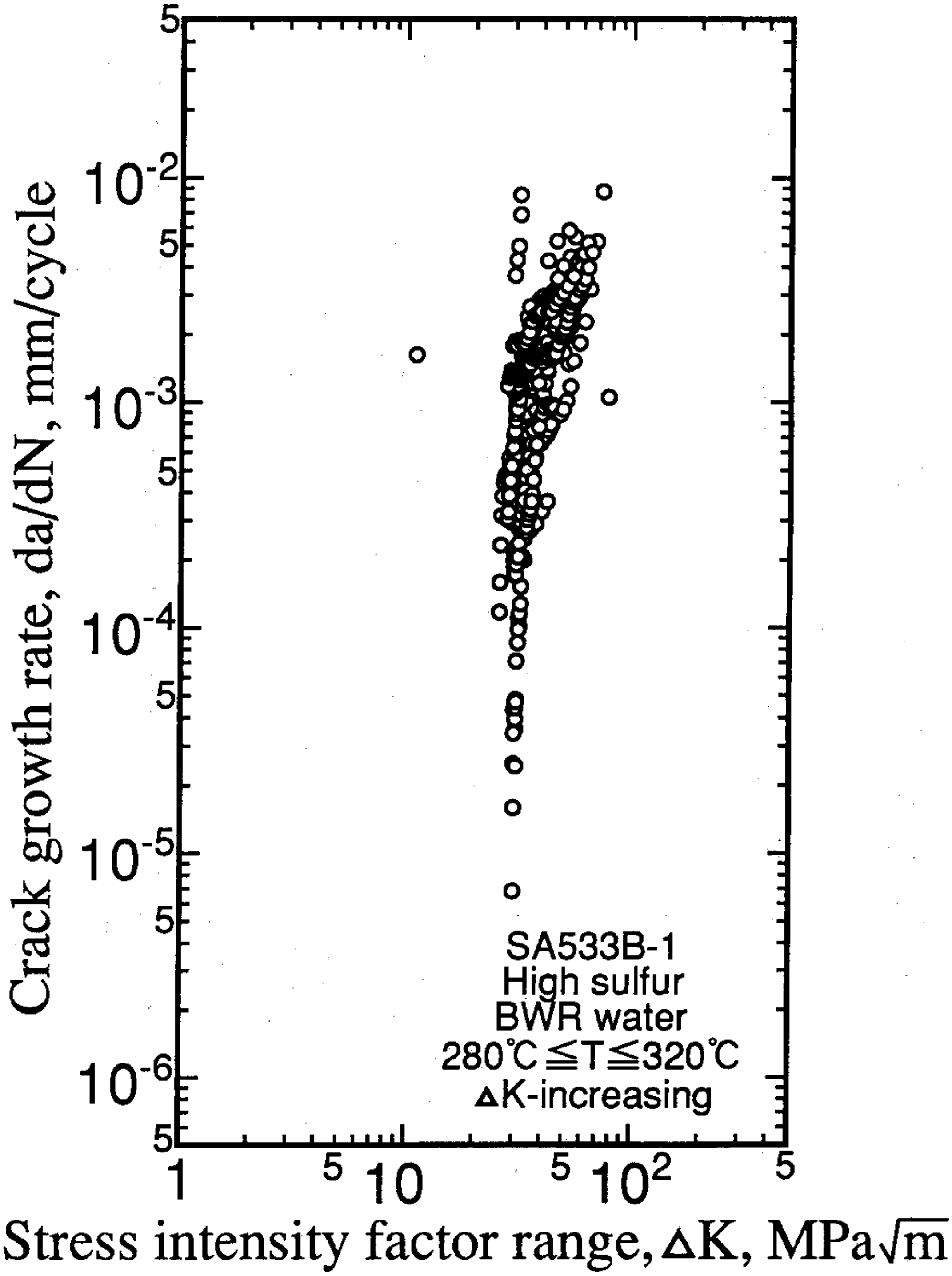

Fig. 9(a) da/dN versus ΔK for SA533B-1 with high sulfur in BWR type water by ΔK-increasing type tests. (data set No.5i)

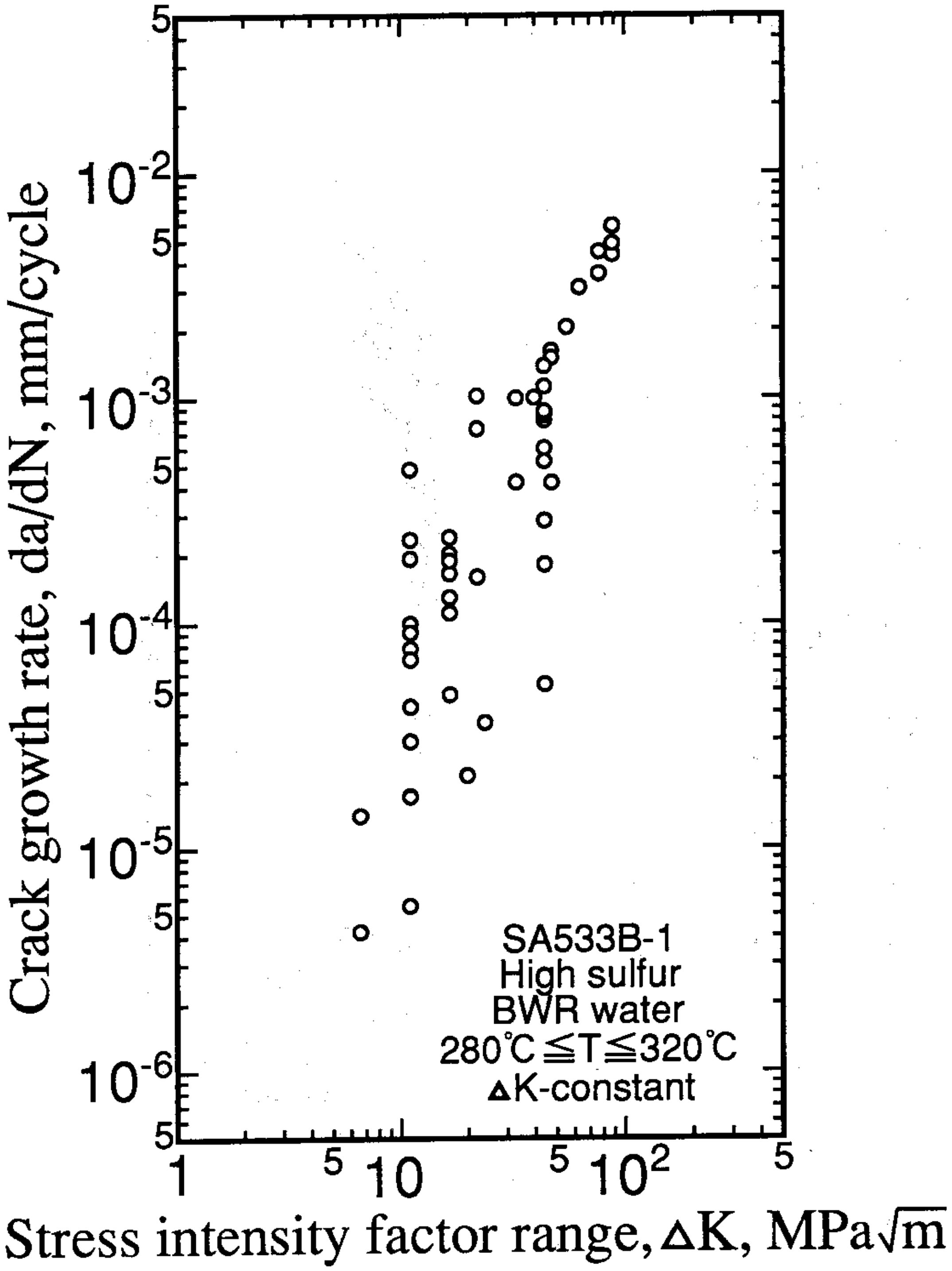

Fig. 9(b) da/dN versus ΔK for SA533B-1 with high sulfur in BWR type water by ΔK-constant type tests. (data set No.5c)

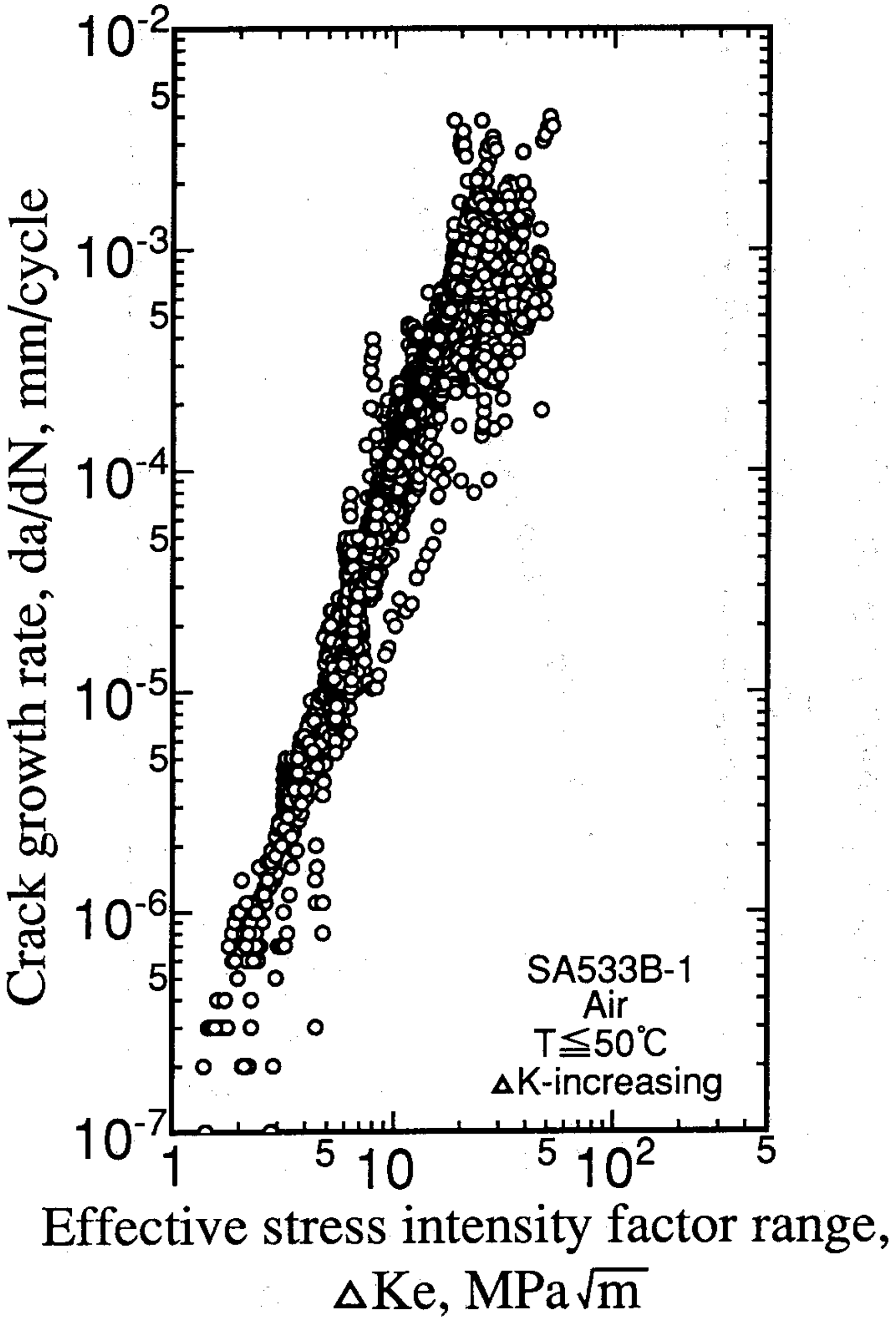

Fig. 10(a) da/dN versus ΔKe for SA533B-1 in air
by ΔK-increasing type tests.
(data set No.1ei)

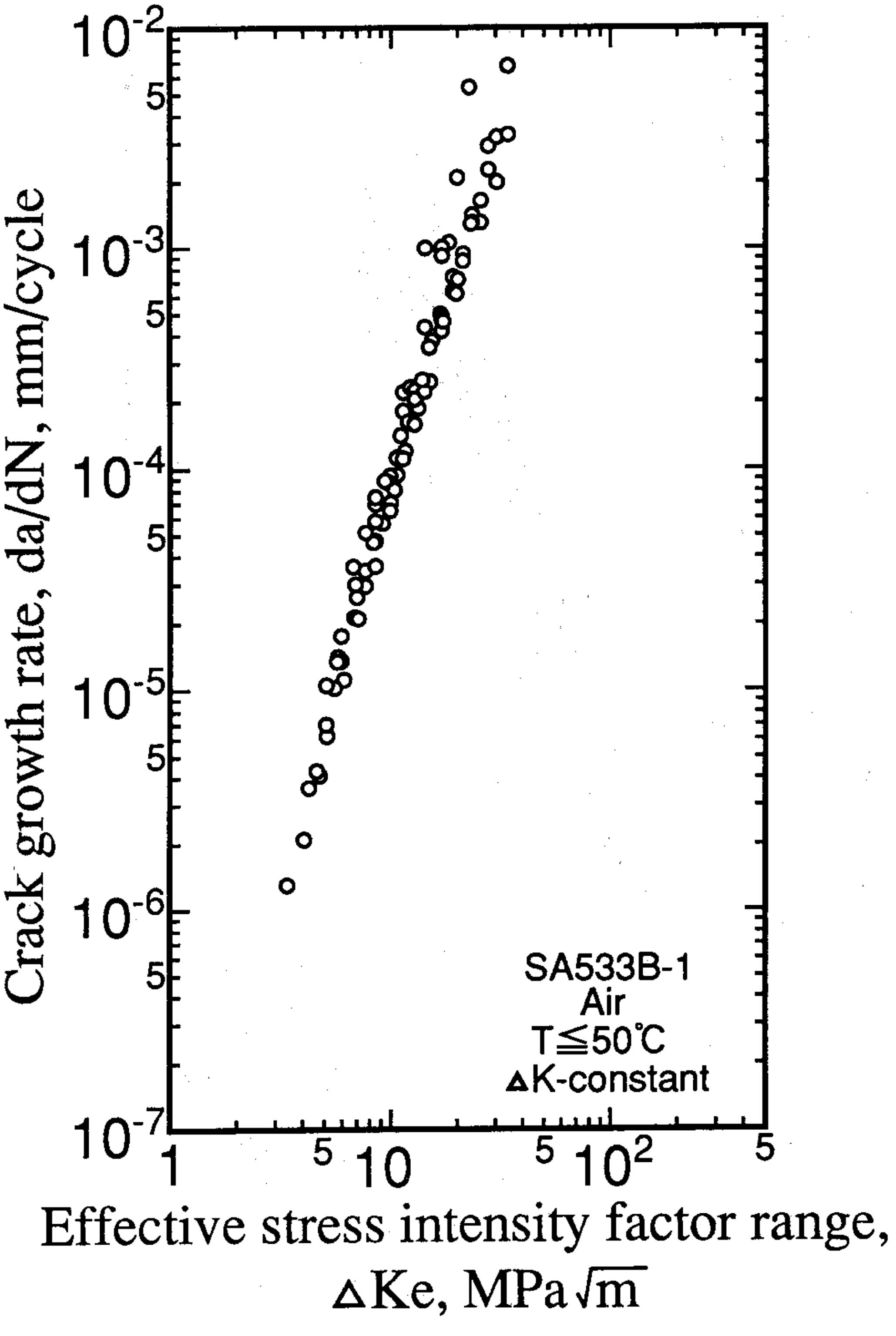

Fig. 10(b) da/dN versus ΔKe for SA533B-1 in air by ΔK-constant type tests. (data set No.1ec)

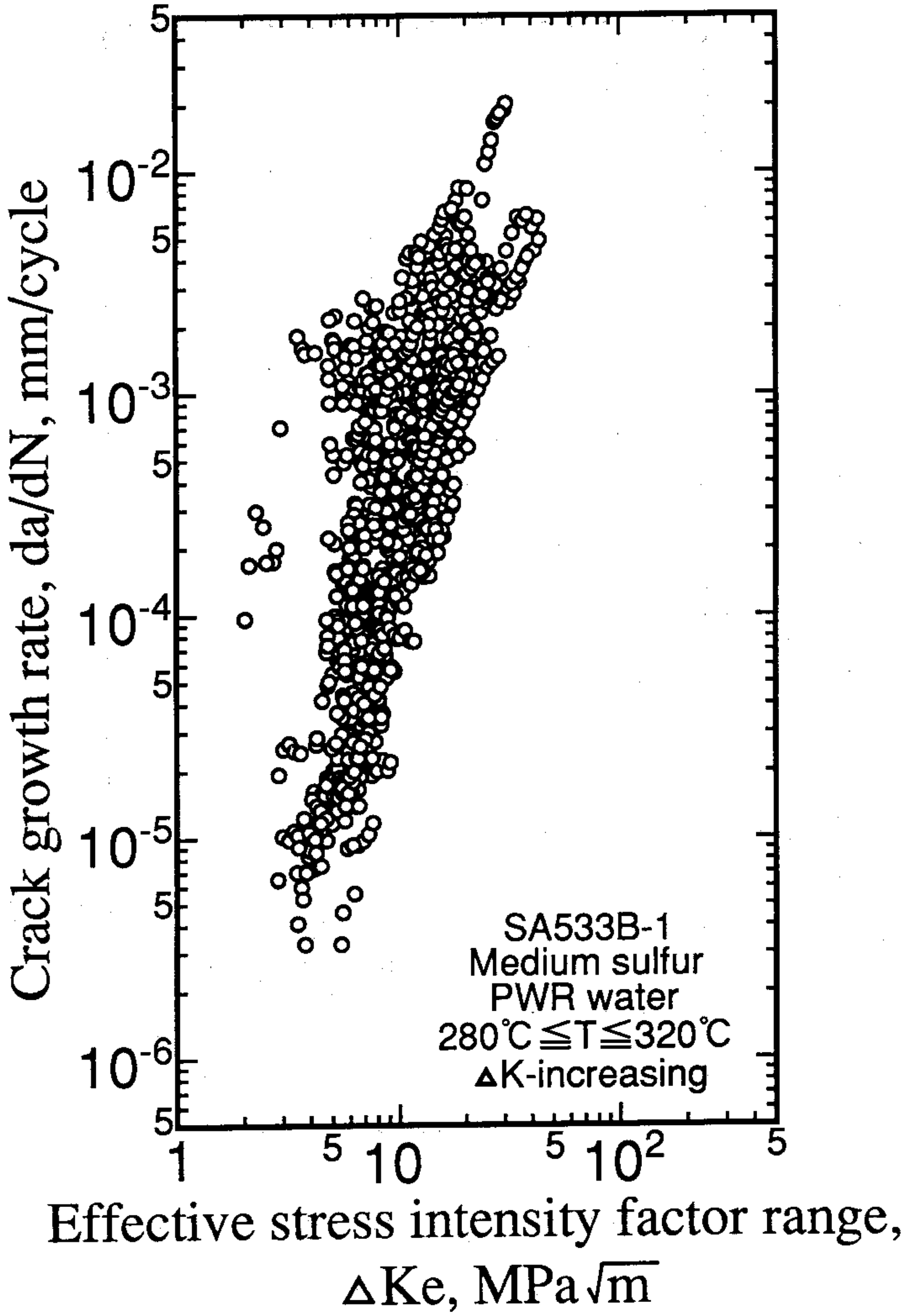

Fig. 11(a) da/dN versus ΔKe for SA533B-1 with medium sulfur in PWR type water by ΔK-increasing type tests. (data set No.2ei)

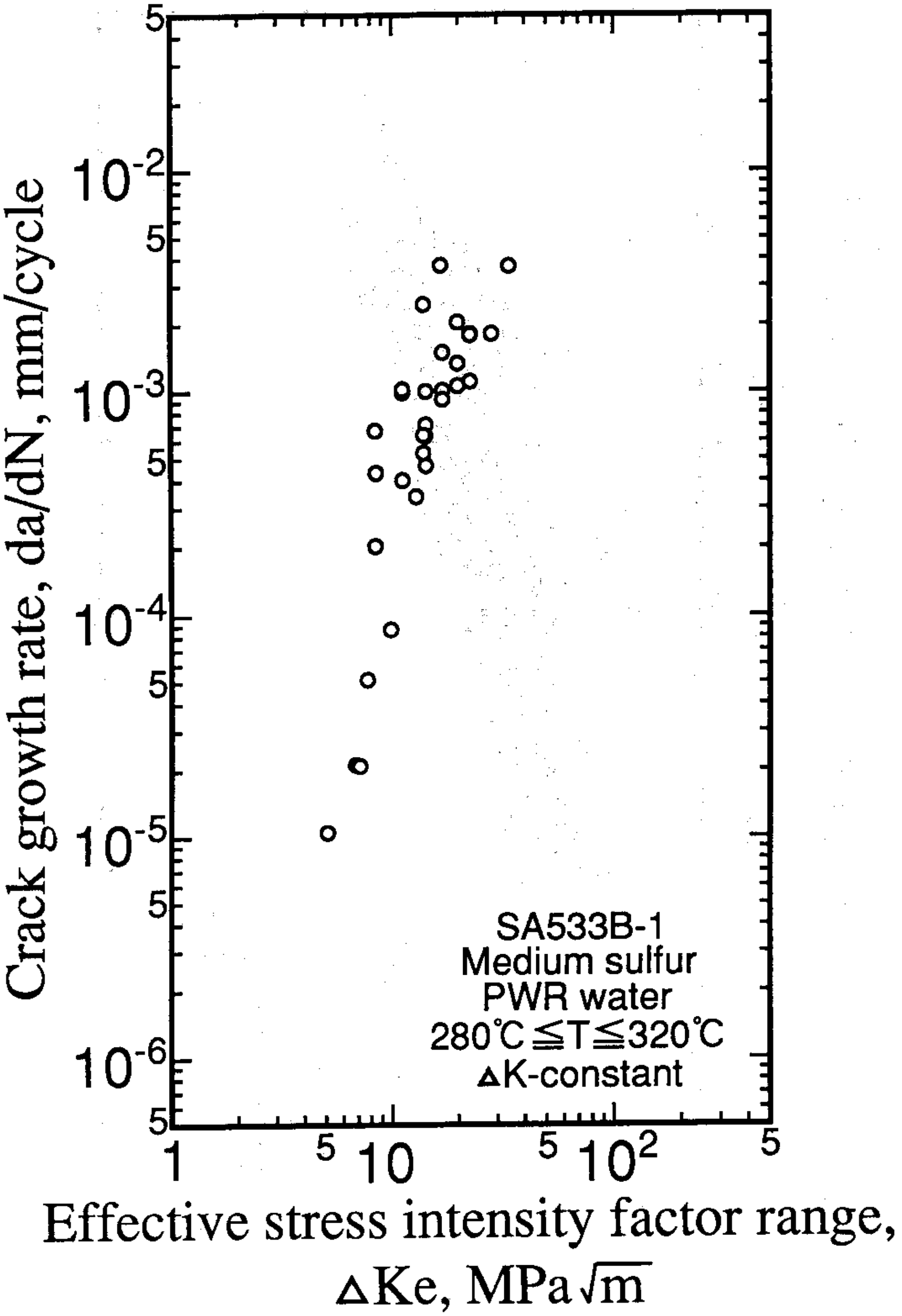

Fig. 11(b) da/dN versus ΔKe for SA533B-1 with medium sulfur in PWR type water by ΔK-constant type tests. (data set No.2ec)

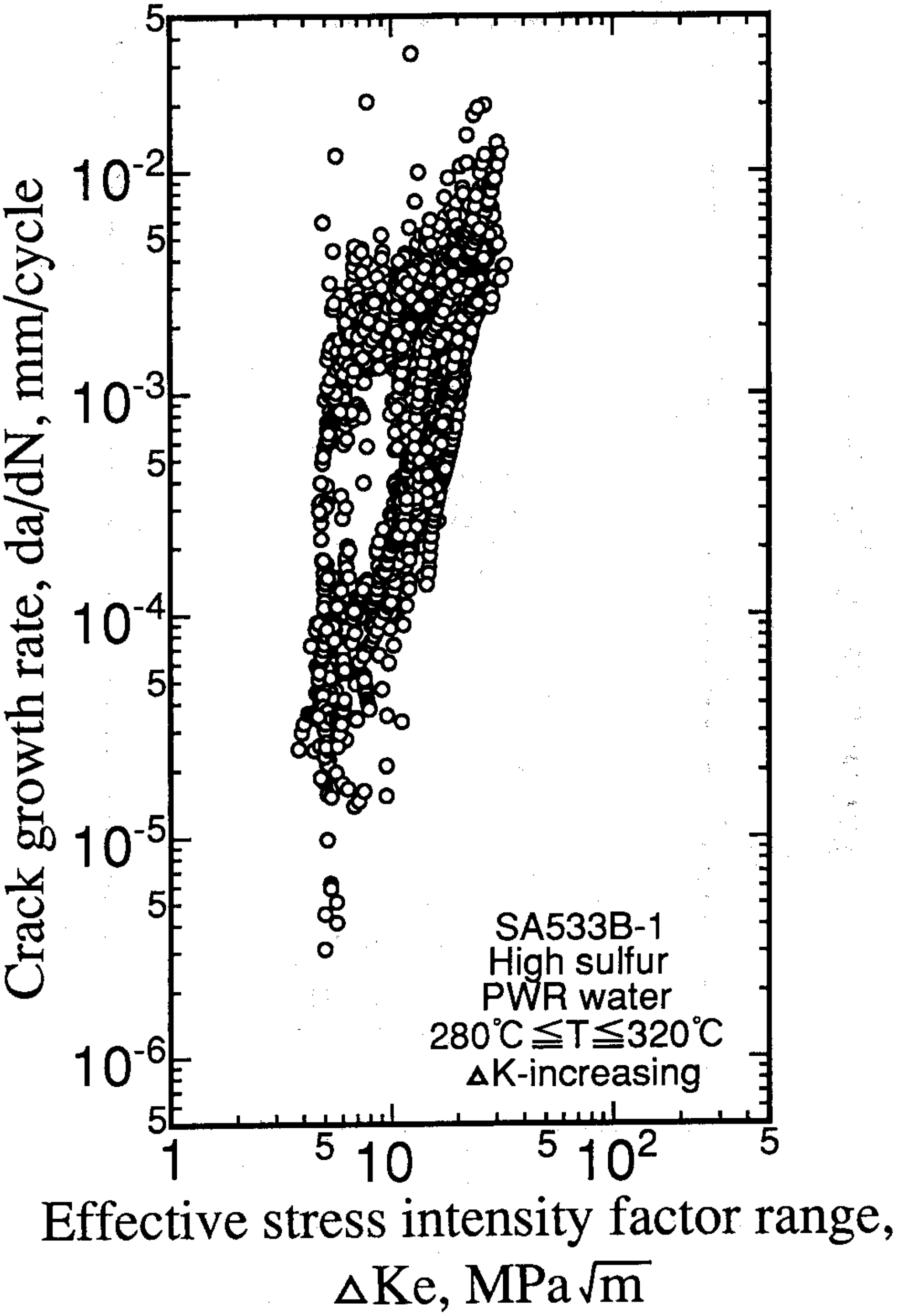

Fig. 12(a) da/dN versus ΔKe for SA533B-1 with high sulfur in PWR type water by ΔK-increasing type tests. (data set No.3ei)

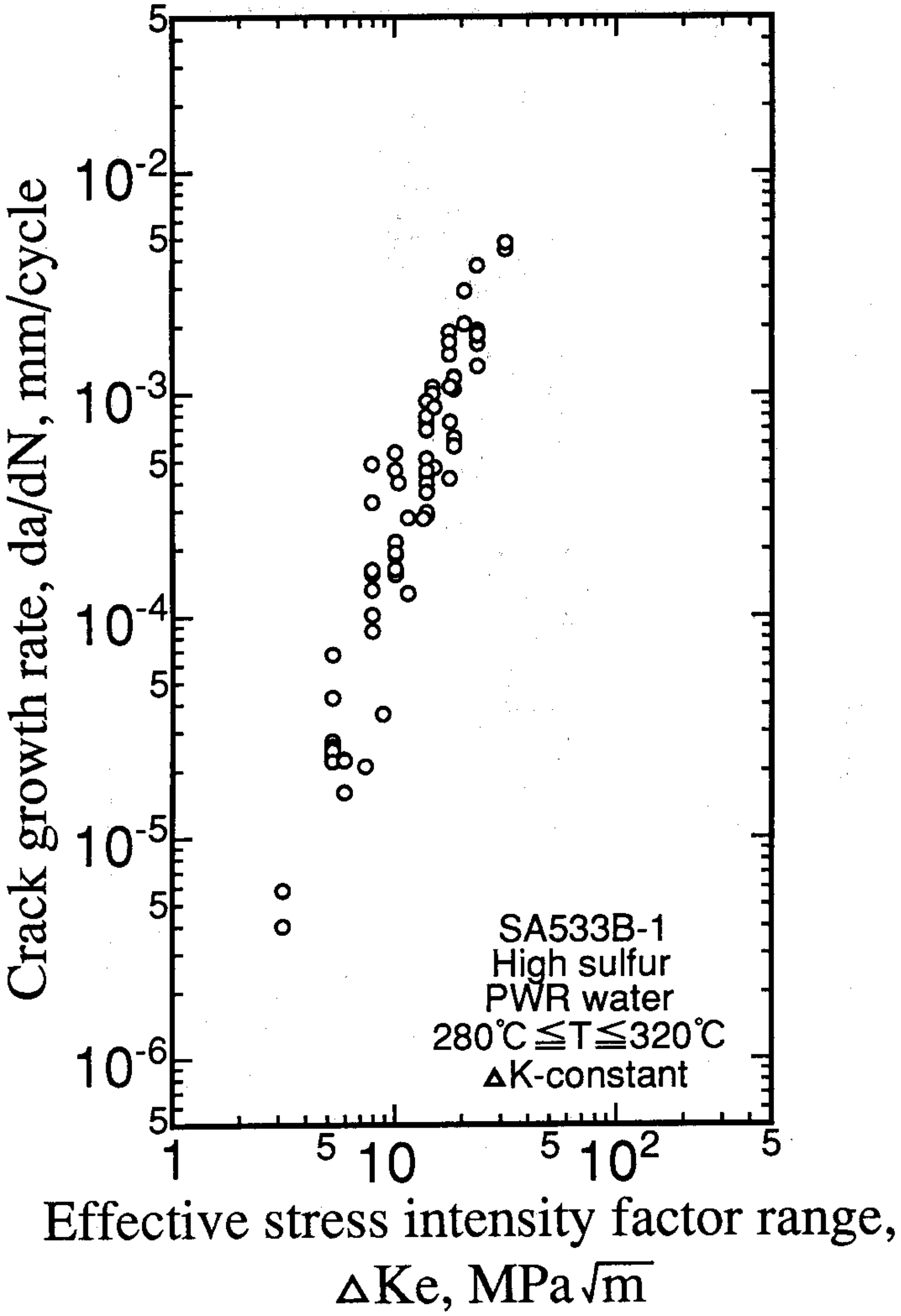

Fig. 12(b) da/dN versus ΔKe for SA533B-1 with high sulfur in PWR type water by ΔK-constant type tests. (data set No.3ec)

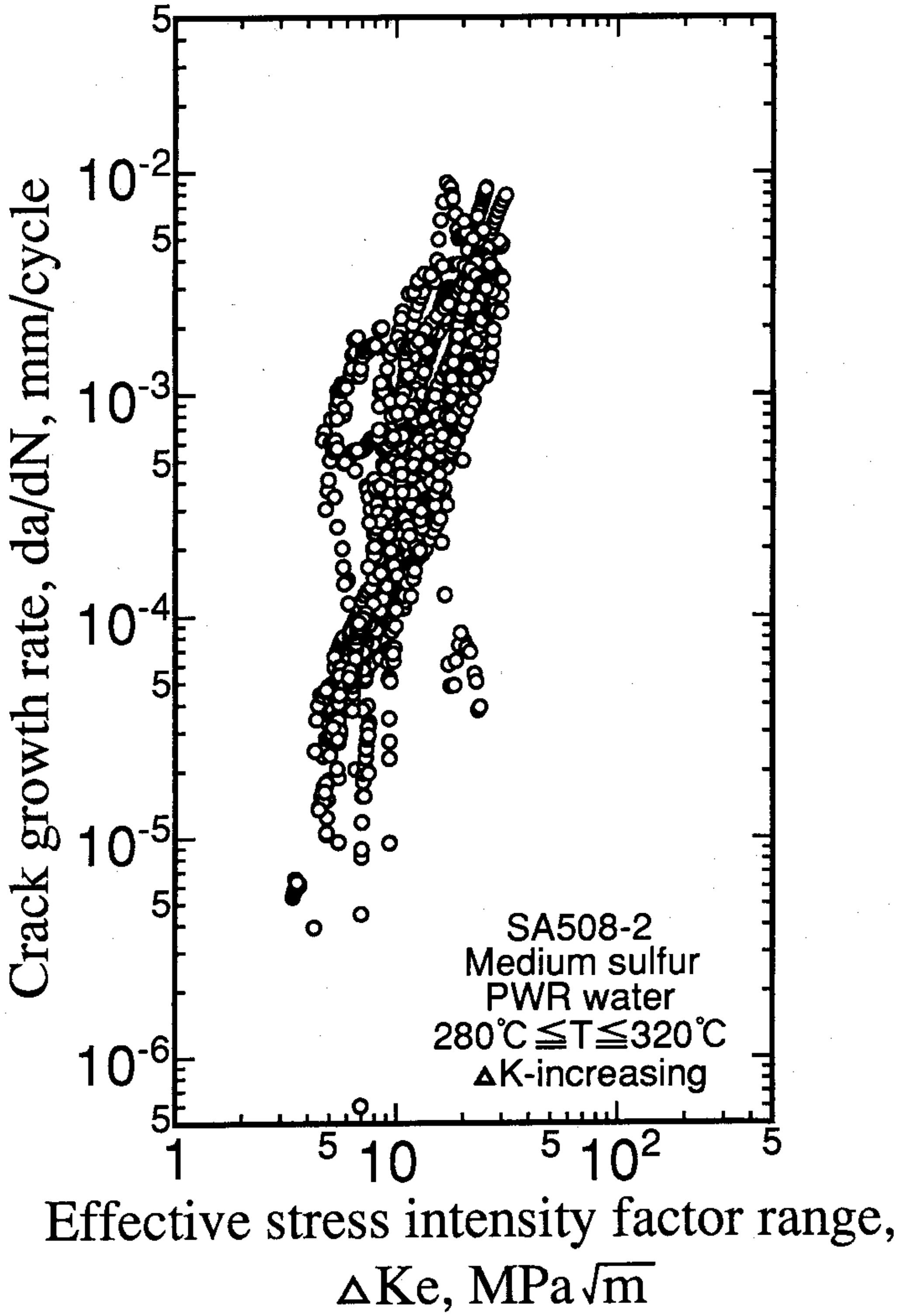

Fig. 13(a) da/dN versus ΔKe for SA508-2 with medium sulfur in PWR type water by ΔK-increasing type tests. (data set No.4ei)

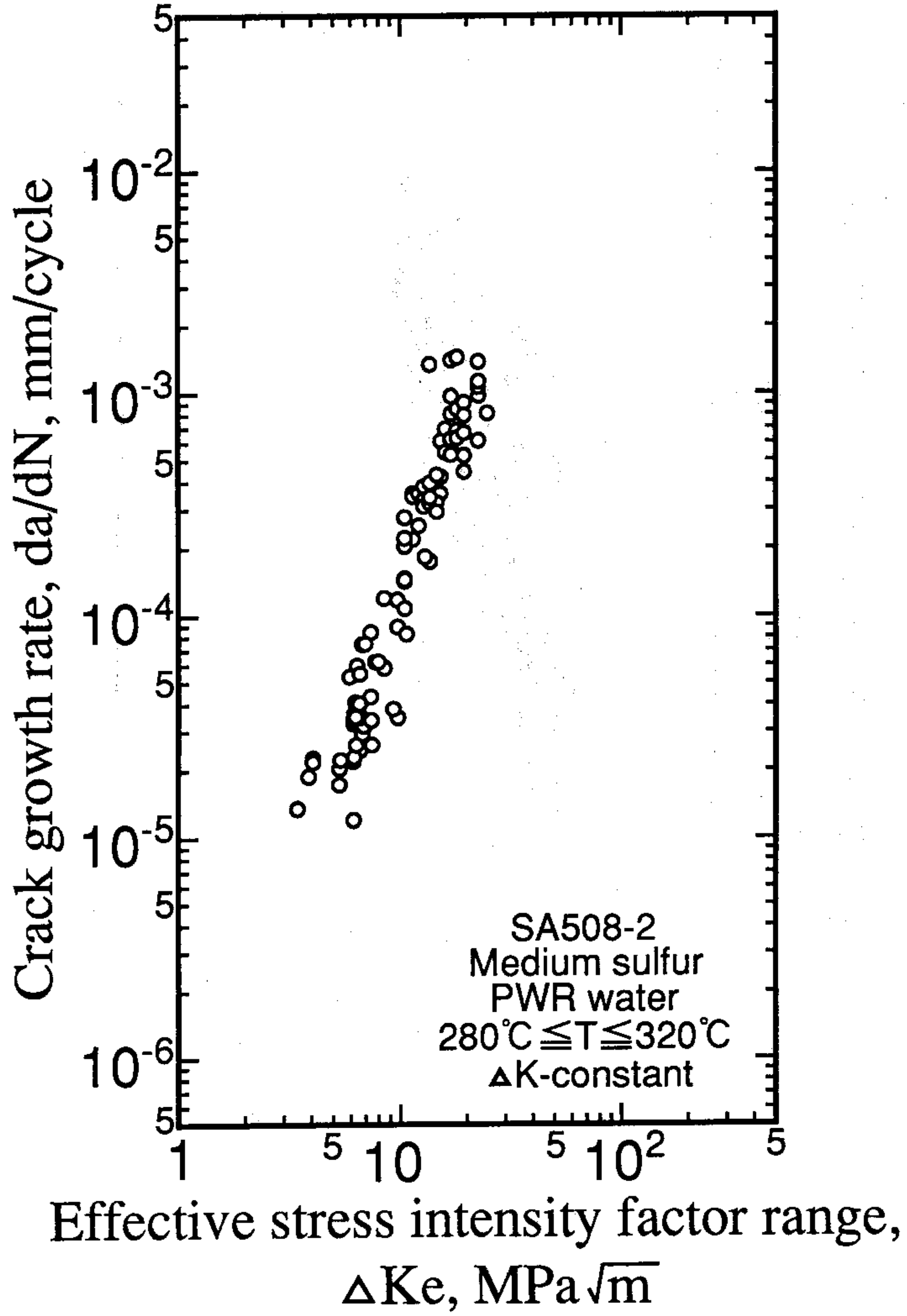

Fig. 13(b) da/dN versus ΔKe for SA508-2 with medium sulfur in PWR type water by ΔK-constant type tests. (data set No.4ec)

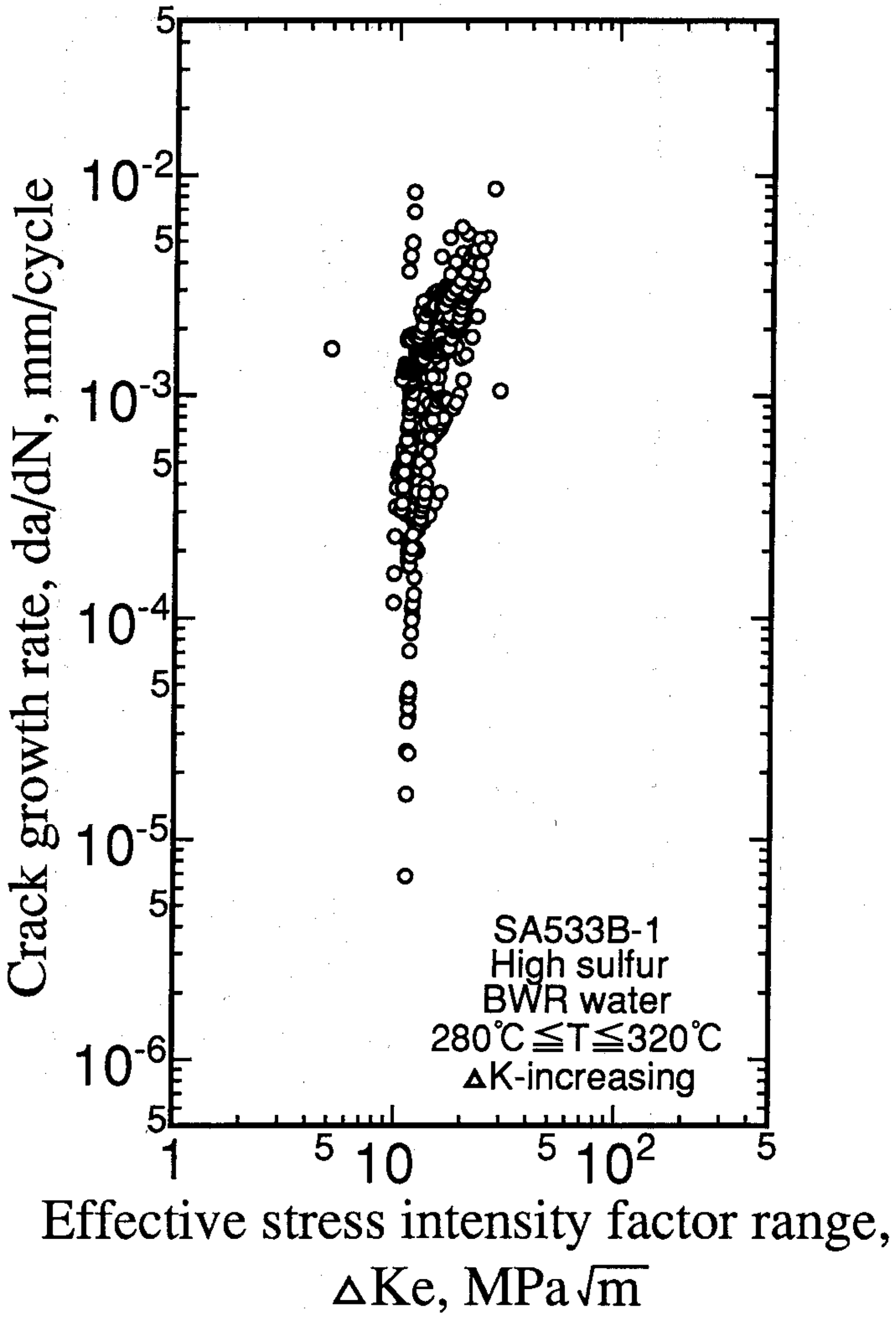

Fig. 14(a) da/dN versus ΔKe for SA533B-1 with high sulfur in BWR type water by ΔK-increasing type tests. (data set No.5ei)

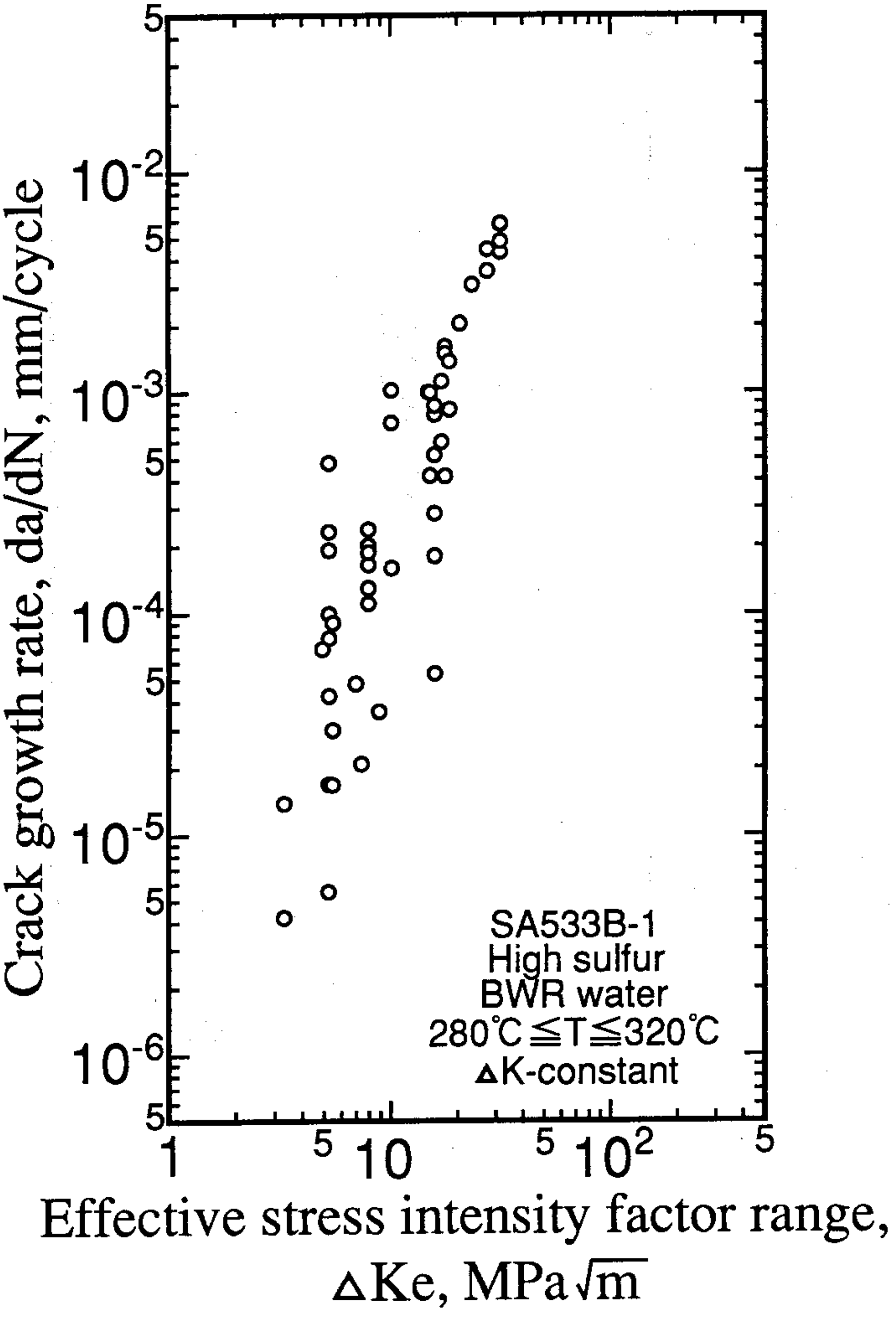

Fig. 14(b) da/dN versus ΔKe for SA533B-1 with high sulfur in BWR type water by ΔK-constant type tests. (data set No.5ec)

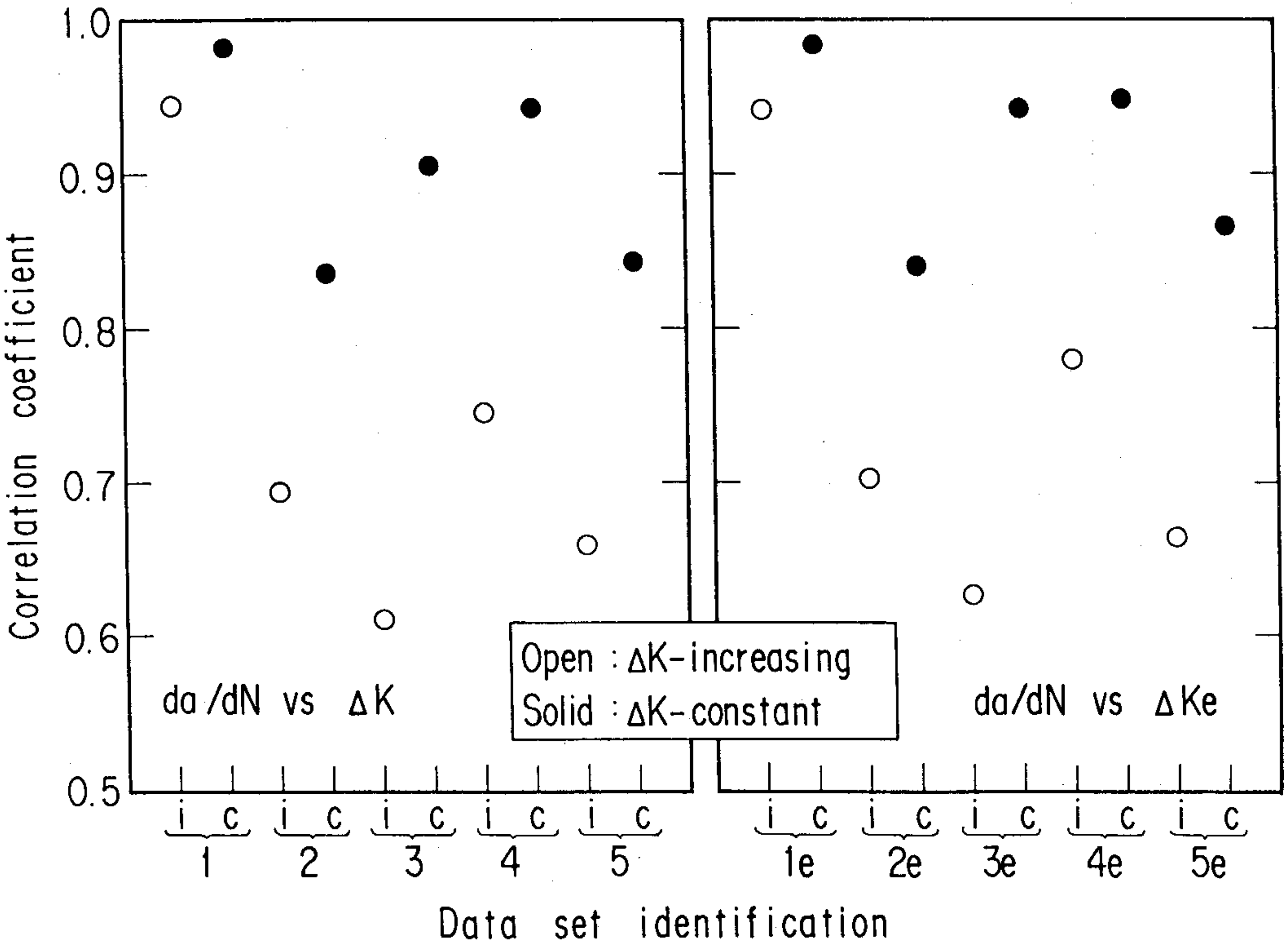

Fig. 15 Correlation coefficients for da/dN versus ΔK and/or da/dN versus ΔKe relations.

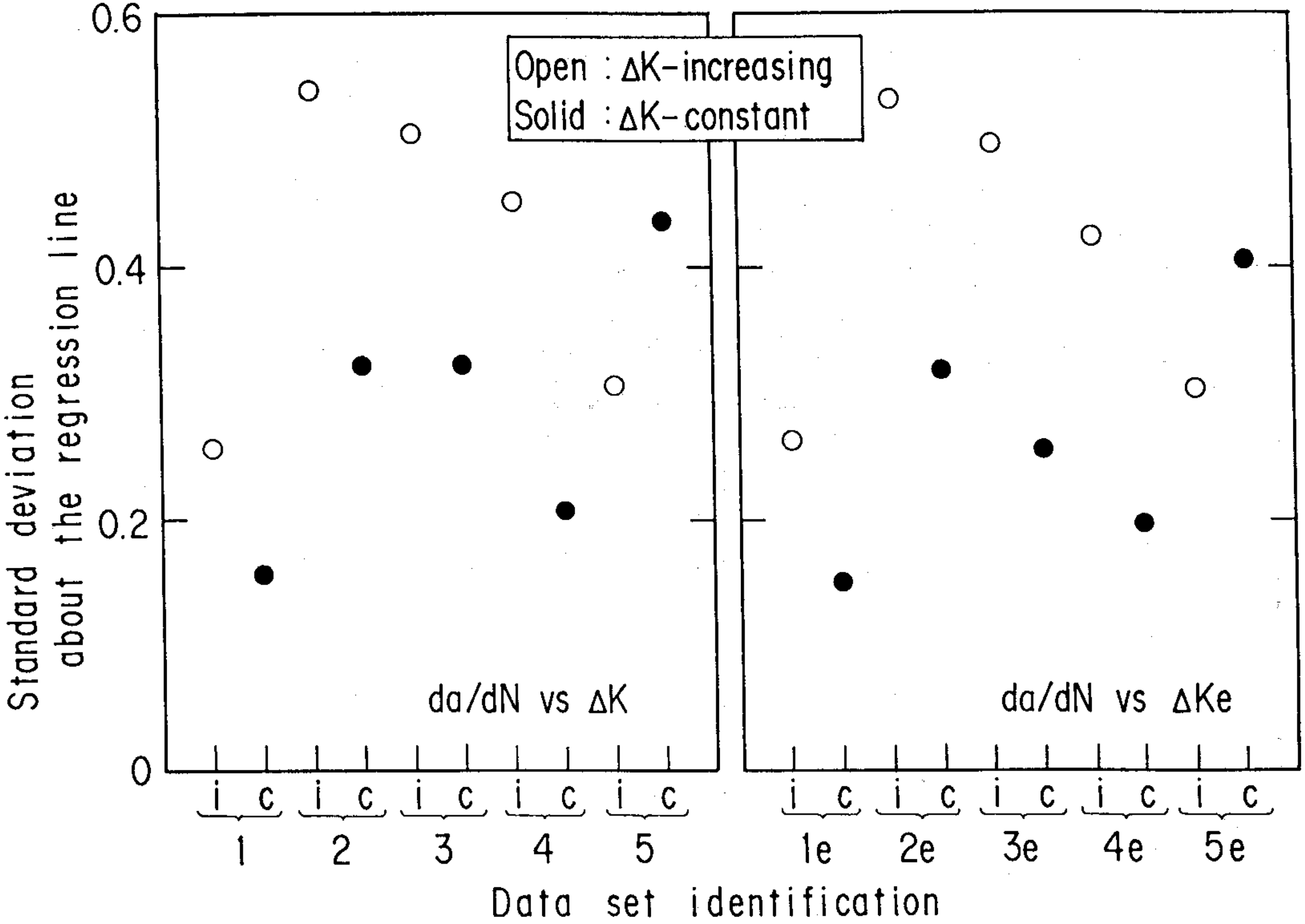

Fig. 16 Standard deviations about regression lines.

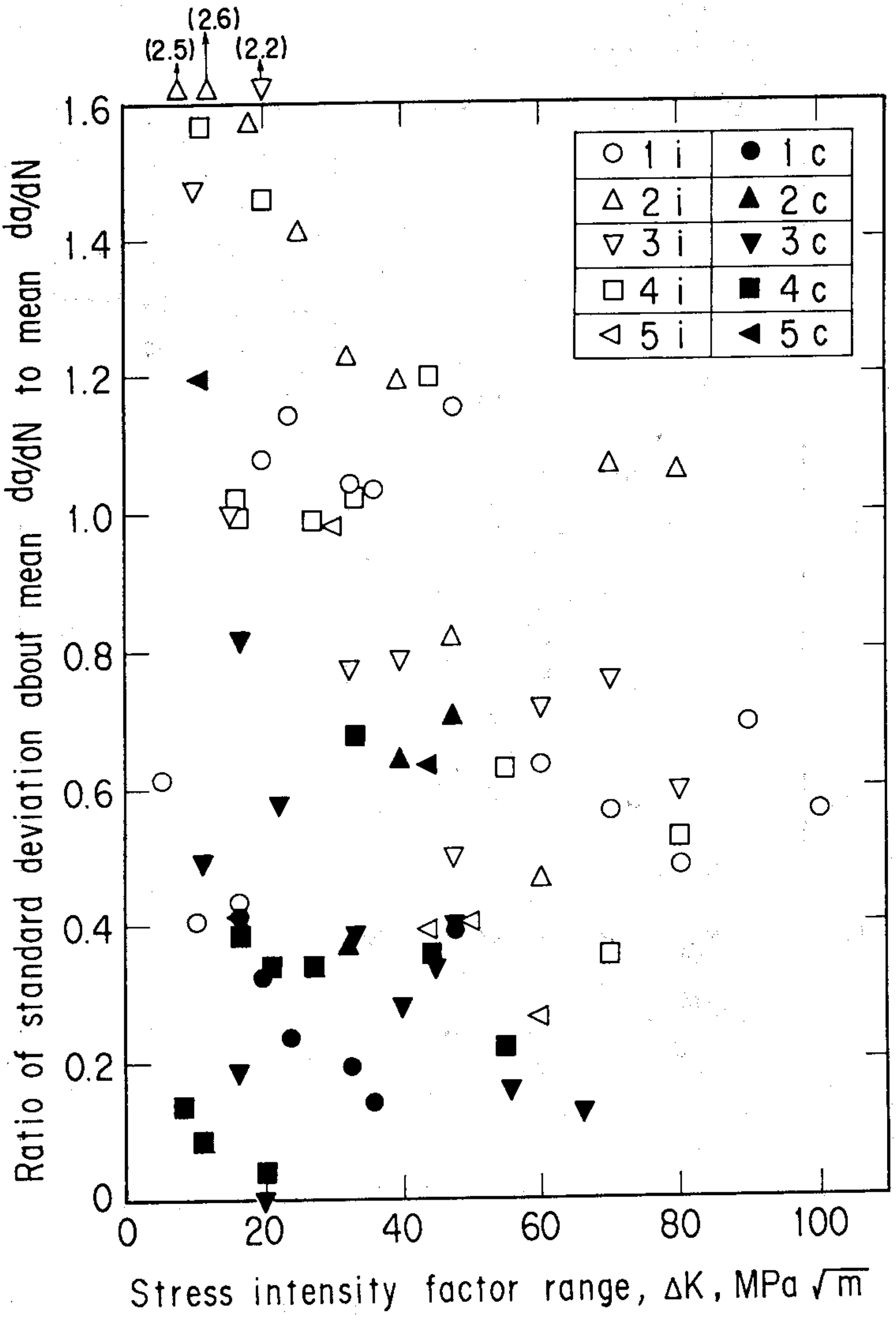

Fig. 17 Standard deviations about mean da/dN at several different ΔK levels for da/dN versus ΔK data.

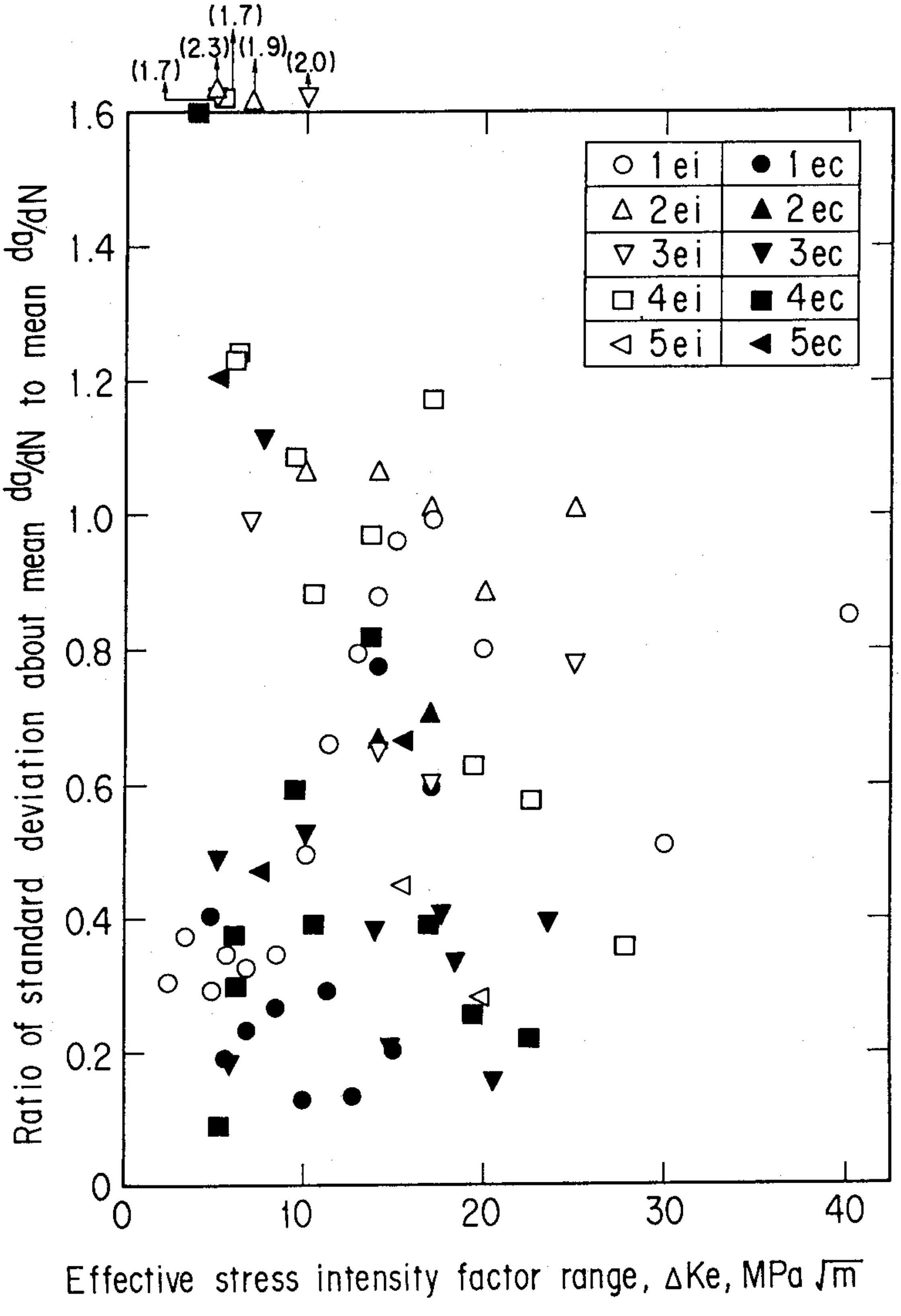

Fig. 18 Standard deviations about mean da/dN at several different ΔKe levels for da/dN versus ΔKe data.