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DEVELOPMENT OF JAERI MATERIAL PERFORMANCE DATABASE (JMPD) AND EXAMPLES OF ITS UTILIZATION

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Development of JAERI Material Performance Database (JMPD) and Examples of Its Utilization

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This paper introduces the present status of the comprehensive material performance database for nuclear applications, which was named JAERI Material Performance Database (JMPD), and examples of its utilization. The JMPD has been developed since 1986 in JAERI with a view to utilizing various kinds of characteristic data of nuclear materials efficiently. Management system of relational database, PLANNER, was employed, and supporting systems for data retrieval and output were expanded. In order to improve user-friendliness of the retrieval system, the menu selection type procedures have been developed where knowledge of the system or the data structures is not required for end-users. As to utilization of the JMPD, three types of data analyses are mentioned as follows:

(1) A series of statistical analyses was performed in order to estimate the yield strength values Sy and the tensile strength values Su of aluminum alloys which are widely used as structural materials for research reactors.

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[*] on leave from Nuclear Energy Data Center

(2) Statistical analyses were accomplished by using the cyclic crack growth rate data for nuclear pressure vessel steels, and comparisons were made on variability and/or reproducibility of the data between obtained by ΔK-increasing and ΔK-constant type tests.

(3) The method of determining the minimum creep rate and the time to onset of the tertiary creep objectively was proposed using creep curve data of high-temperature alloys.

Keywords: Material Performance Database, Relational Database, Aluminum Alloy, Pressure Vessel Steel, High-temperature Alloy, Yield Strength Values, Tensile Strength Values, Cyclic Crack Growth Rate, Stress Intensity Factor Range, Statistical Analysis, Variability, Creep Curve, Minimum Creep Rate, Time to Onset of Tertiary Creep

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原子力材料総合データベース（JMPD）の開発とその利用例

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日本原子力研究所では，原子力施設用材料のさまざまな特性データを効率的に利用することを目的として，1986年から原子力材料総合データベース（JMPD）の開発・整備を進めてきた。本稿では，JMPDの概要及びその利用例を紹介する。

JMPDは，大型計算機のリレーショナルデータベースであるPLANNERを用いて，データの入力と管理を行い，これを中核として，検索支援システムの充実が図られている。必要なデータを容易に検索できるようにするために，利用者がデータ構造やデータ内容に精通していなくても，メニュー選択方式で目的とする検索が可能なシステムを新たに作成した。

JMPDの利用例に関しては，以下の3種類のデータ解析について述べる。

(1)　試験研究炉用アルミニウム合金の設計降伏点（Sy）及び設計引張強さ（Su）の検討

(2)　原子炉圧力容器鋼の疲労き裂成長速度のばらつき／再現性と△K増加型あるいは△K一定型といった試験モードの差との関係に関する統計解析

(3)　耐熱合金のクリープ曲線データから最小クリープ速度及び3次クリープ開始点を客観的に決定する方法の提案

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1. Introduction

Based on the recent remarkable improvement of the computational environment, massive and quick communications for complex materials data are able to extract attractive and sophisticated information easily and timely. These improvements are also leading to other advancements such as graphic display, statistics evaluation, networking capabilities etc. Many groups are now developing computerized material databases to make available to general properties data for metals, alloys, composites etc. [1-4]. Referring to the critical and technical assessment on the research and development in the field of nuclear technologies [5], promotion of advanced material research which could bring about technical breakthroughs in many research fields have to be encouraged. In accordance with this new trend, a comprehensive material performance database, which was named JAERI (Japan Atomic Energy Research Institute) Material Performance Database (JMPD), has been developed since 1986 focussing on the data stored through research and development promoted by JAERI.

This paper introduces the present status of the JMPD [6], and three examples of its utilization.

2. Outline of JMPD [6]

Basic studies were initiated for developing new concepts and mechanisms for comprehensive data evaluation of materials for nuclear applications and their handling systems. Based on a survey made to understand the present status and key issues of existing activities relevant to material databases, significance of both the flexibility of data structure and user-friendliness of the system was highly emphasized to achieve the requirements of the system.

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Referring to more than ten databases which have been already developed as comprehensive databases in Japan and foreign countries [7-9], tentative data structure for metallic materials was originally determined in a three-level hierarchy. The outline of the three-level hierarchical data structure is shown in Fig.1. Six categories such as data source, material, specimen, test method & data reduction, test condition, and test result, were classified into the primary level. Twenty-five tables were considered to be in the secondary level. More than 420 data items were prepared for the tertiary level.

The concept of the JMPD is schematically illustrated in Fig.2. In the figure the newly developed part is shown as a shadowed portion. Management system of relational database, PLANNER which is supported on the mainframe, was chosen from the viewpoints of easy retrieval of the necessary data and easy updating of the data. Functions of supporting system for data retrieval, graphic description, statistics and specific analyses were expanded. The supporting system for data retrieval was extensively intensified to improve user-friendliness which may play an important role to extract useful information from complex mixture of materials data. Main features of the newly developed system for data retrieval are as follows:

(1) Knowledge of the system or the data structures is not required for end-users.

(2) The system can be easily adapted to the changes of significance of data items which strongly depends on the progress of research and development.

To clarify the merits of this system, Fig.3 shows a comparison between a typical retrieval procedure based on the Structured Query Language (SQL) and the newly developed menu selection type procedure to solve a representative question. It is clearly shown that users can easily extract important information when they access the newly developed one. Functions of unit conversion, inspection of the stored data, help etc. were also supported for further improvement of user-friendliness of the system.

The data stored in the JMPD by the end of August 1993 are listed in

Fig.4, in which the data from more than 7800 test pieces are prepared for data evaluation. The data stored were checked through the authors' review in order to prevent the unexpected misinput within the range of possibility. Only the data of the materials whose origin such as chemical compositions and heat treatment conditions as well as experimental methods are clear have been stored.

3. Analyses and Evaluations of Material Data through JMPD

The following three types of data analyses were performed utilizing the JMPD;

(1) evaluation of the yield strength values Sy and the tensile strength values Su of aluminum alloys for research reactors [10,11],

(2) statistical analyses of variability and/or reproducibility of environmentally assisted cyclic crack growth rate data for nuclear pressure vessel steels relative to ΔK (stress intensity factor range) control modes [12-14], and

(3) proposal of the method of determining the minimum creep rate and the time to onset of the tertiary creep objectively using creep curve data of high-temperature alloys [15].

3.1 Evaluation of Sy and Su of Aluminum Alloys for Research Reactors [10,11]

Aluminum alloys are frequently used as structural materials of research reactors. Although the material strength standards such as the yield strength values Sy and the tensile strength values Su are necessary for "design by analysis", the material strength standards for those materials have not been determined yet.

Hence a series of tension tests was performed and the results were statistically analyzed with the aim at generating the above-mentioned design values. The procedures applied to the present program were as

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Hence a series of tension tests was performed and the results were statistically analyzed with the aim at generating the above-mentioned design values. The procedures applied to the present program were as follows:

(1) Based on actual use for research reactors in Japan, actual manufacture in Japan, possible use in the future reactors etc., A1100P-O, A5052P-O, A5052BE-O, A6061P-T6 (T651 for a thick plate), A6061BE-T6 and A6063BE-T6 were selected as the test materials for the present program.

(2) The tests were conducted on eight heats per material at temperatures ranging from room temperature (RT) to 200°C at every 50°C in principle.

(3) The specimens were prepared according to the Japanese Industrial Standards (JIS) Z 2201 [16].

(4) The tests were performed using the test procedures recommended in JIS G 0567 [17] in principle.

(5) The data obtained were stored in the JMPD.

And the values of Sy and Su were determined on the basis of the test results as follows:

(1) All the values of 0.2% proof stress (or ultimate tensile strength (UTS)) are normalized with dividing them by the mean value obtained at RT for the same heat of the material.

(2) The best fit curve for the normalized values is evaluated with the least square method in a third-order polynomial expression as a function of test temperature for each material. The evaluated curve is called Curve A.

(3) Minimum position values (MPVs) are evaluated with multiplying the values of Curve A by Sy (or Su) at RT, which is defined as the minimum value indicated in JIS H 4000 [18] or in JIS H 4040 [19].

(4) Curve B is determined along the MPV curve in such a way not only that the values at higher temperatures should not be higher than those at lower temperatures, but also that the values should not be higher than 1% probable values of yielding (or fracture) at each temperature based on the test results.

(5) Sy (or Su) is determined as the values of Curve B.

The computer program performing the above-mentioned procedure was registered in the JMPD, and the stored data were statistically analyzed through the menu selection type procedure. Based on the statistically analyzed results the draft of Sy and Su was evaluated. Figure 5 is an example of plotting on normal probability paper for UTS of A1100P-O at RT. Figure 6 is the draft of Sy and Su for A1100P-O.

The draft was compared with MITI No.501[*1] as well as the ASME Codes, and the trend of the available data was also examined. It was revealed that the draft could be adopted as the material strength standards, and that the values of the draft at and above 150°C for A6061-T6 and A6063-T6 could be applied only to the reactor operating conditions III and IV[*2]. And the draft, which is shown in Table 1, has already been adopted in the Science and Technology Agency regulatory guide as standards for structural design of nuclear research plants.

3.2 Statistical Analyses of Variability/Reproducibility of Environmentally Assisted Cyclic Crack Growth Data Relative to ΔK Control Modes [12-14]

A lot of cyclic crack growth rate data for nuclear pressure vessel steels have been accumulated mainly through the activity of the International Cooperative Group on Cyclic Crack Growth Rate Testing and Evaluation (the ICCGR Group) [20-22]. The data have been stored in the JMPD. Most of them were obtained by the commonly used constant-load-amplitude (ASTM E647 [23] based) tests, i.e., ΔK-increasing type tests, while those by ΔK-constant type are less common.

In general, 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

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[*1] The notification No. 501 of the Ministry of International Trade and Industry, i.e., the structural design code for power reactors in Japan.

[*2] The reactor operating conditions III and IV correspond to emergency and faulted conditions, respectively.

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 a comparison between ΔK-increasing and ΔK-constant type tests. In fact, an appreciable difference between those was already observed by the authors through the fatigue crack growth tests for a low alloy steel SA533B-1 in air [24]. 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.

All the data of cyclic crack growth rate on low alloy steels stored in the JMPD were classified into 14 categories based on material and test environments as shown in Table 2. A preliminary survey revealed that some data groups should be omitted from the analyses due to their inadequacy of the sample size as summarized in Table 2. The data of five categories shown in Table 3, therefore, 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 [25];

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

where R is Kmin/Kmax.

Statistical analyses were conducted separately for the data obtained by ΔK-increasing and by ΔK-constant type tests. Figure 7 shows a comparison based on the data obtained in air environment. Figure 8 shows examples of da/dN versus ΔK relations for SA508-2 steel in simulated PWR (pressurized water reactor) primary coolant. The data set identification and the number of the data sets analyzed are shown in Tables 3 and 4, respectively.

The following three sorts of statistical analyses were conducted;

(1) correlation coefficients for da/dN versus ΔK and/or da/dN versus ΔKe (see Fig. 9),

(2) standard deviations about the regression lines (see Fig. 10), and

(3) standard deviations about the mean da/dN at several different ΔK levels (see Figs. 11 and 12).

Based on the analytical results, 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 (light water reactor) primary coolants than those in air.

(3) Variability is larger at lower ΔK levels, especially in the data obtained 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.

3.3 Proposal of Method of Determining Minimum Creep Rate and Time to Onset of Tertiary Creep Using Creep Curve Data [15]

A nickel-base heat-resistant alloy, Hastelloy XR [26], was developed as the structural material for high-temperature components of the Japanese first HTGR, i.e., the High-Temperature Engineering Test Reactor (HTTR). Creep data on the alloy have been accumulated and stored in the JMPD. Creep curves of the alloy were analyzed by utilizing the JMPD.

In the analyses of creep curves, the following Garofalo formula (Eq. (2)) [27] for the primary and the secondary creep stages and the following Kachanov-Rabotonov formula (Eq. (3)) [28] for the tertiary creep stage were applied, because the applicability of these formulas to creep curves on Hastelloy XR was known to be fairly good [29-32].

$$\varepsilon = at + b\{1-\exp(-ct)\} \qquad \text{for} \quad 0 \le t \le t_3 \qquad (2)$$

$$\varepsilon = at_3 + b\{1-\exp(-ct_3)\} + a\int_{t_3}^{t}\left(\frac{t_R-t}{t_R-t_3}\right)^n dt \qquad \text{for} \quad t_3 \le t \le t_R \qquad (3)$$

were ε is creep strain, "t" is time, t_3 is the time to the onset of the tertiary creep, t_R is the time to rupture, and "a", "b", "c" and "n" are constants.

When these formulas are applied, the visual fitting method from ε versus "t" or $\dot{\varepsilon}$ versus "t" plots is usually adopted to determine the time to the onset of the tertiary creep t_3 and/or the minimum creep rate "a". Such a method, however, is not preferable for the precise evaluation of many creep curves. Hence a simple and useful method different from visual fitting was proposed in the present study.

In the proposed method a range of the data which belongs to the secondary creep is determined as follows.

All the t-ε pairs existing on the right side of the datum point which gives the minimum ε/t belong to the tertiary creep, and all the t-ε pairs existing on the left side of the datum point which gives the minimum $(\varepsilon_R-\varepsilon)/(t_R-t)$ belong to the primary creep, where ε_R is rupture elongation (see Fig. 13). The secondary creep stage can be considered from the datum point which gives the minimum $(\varepsilon_R-\varepsilon)/(t_R-t)$ to the datum point which gives the minimum ε/t for convenience sake.

Constants "a" and "b" in Eqs. (2) and (3) are determined as ε=at+b with the least squares method using all the data which belong to the secondary creep. Thus the minimum creep rate is determined as the slope of the line, i.e., the value "a". With fixing the values "a" and "b" to be the values determined above, constant "c" in Eq. (2) is determined with the least squares method using all the t-ε pairs existing on the left side of the datum point which gives the minimum $(\varepsilon_R-\varepsilon)/(t_R-t)$. With fixing the values "a" and "b" to be the values determined above in like manner, the values of t_3 and "n" in Eq. (3) are determined with the least squares method using all the t-ε pairs existing on the right side of the datum point which gives the minimum ε/t, providing that the point t_3 exists between the datum point which gives the minimum ε/t and the next datum point. Thus the time to the onset of the tertiary creep t_3 is determined.

Figure 14 shows examples of creep curves on Hastelloy XR obtained in the simulated HTGR helium environment [33] and the result of evaluation by the above-mentioned method.

In the future, applicability of other techniques such as the θ projection method [34,35] or its modified method [36] to the creep curves of Hastelloy XR will be examined.

4. Summary and Outlook for Future

JAERI Material Performance Database (JMPD) has been developed paying attention to maintain substantial user-friendliness of the system. The present status of the system and three examples of its utilization were described briefly. They are evaluation of the design values of aluminum alloys for research reactors, statistical analyses of variability and/or reproducibility of cyclic crack growth rate data on pressure vessel steels and proposal of the method of determining the minimum creep rate and the time to onset of the tertiary creep objectively using creep curve data of high-temperature alloys.

As for the future direction of the JMPD, following important points can be emphasized:

(1) A data networking system has to be incorporated to provide engineers and scientists with easy online access to other sources of reliable well-documented, numerical and/or factual material property data. The

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pilot distributed system for such a networking is under construction named Data-Free-Way [37].

(2) Even if the materials database system is designed as a distributed system, e.g., a set of high performance workstations on networking environment, it will be also important to set a main system for uploading from contributors and downloading to users. This capability may lead many advantages such as easier access and application, easier homogenization of data structures etc., through their own familiar computers.

(3) One of the most important advantages of computerized material database is the possibility of data evaluation of the retrieved data set. Therefore some typical application programs of data evaluation will be incorporated further.

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Table 1 Draft of yield strength values Sy and tensile strength values Su of aluminum alloys for research reactors.

Material		-30～40℃	75℃	100℃	125℃	150℃	175℃	200℃
A1100P-O	Sy (MPa)	25	19	19	18	17	15	12
	Su (MPa)	74	64	59	54	48	42	34
A5052P-O	Sy (MPa)	64	55	55	55	54	53	52
	Su (MPa)	177	171	168	159	147	133	118
A5052BE-O	Sy (MPa)	69	55	55	55	54	53	52
	Su (MPa)	177	171	168	159	147	133	118
A6061BE-T6	Sy (MPa)	245	237	231	225	(217)	(207)	(194)
	Su (MPa)	265	253	245	236	(226)	(214)	(201)
A6061P-T6, T651	Sy (MPa)	245	237	231	225	(217)	(207)	(194)
	Su (MPa)	294	267	258	249	(238)	(226)	(212)
A6063BE-T6	Sy (MPa)	177	160	155	152	(146)	(137)	(124)
	Su (MPa)	206	170	164	157	(149)	(139)	(128)

The values in the parentheses can be applied only to the reactor operating conditions Ⅲ and Ⅳ.

Table 2 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 3 Data set identification.

1 i	ΔK-increasing	SA533 B-1	Air	da/dN versus ΔK
1 c	ΔK-constant			
2 i	ΔK-increasing	SA533 B-1 Medium S	PWR water	
2 c	ΔK-constant			
3 i	ΔK-increasing	SA533 B-1 High S		
3 c	ΔK-constant			
4 i	ΔK-increasing	SA508 - 2 Medium S		
4 c	ΔK-constant			
5 i	ΔK-increasing	SA533 B-1 High S	BWR water	
5 c	ΔK-constant			
1 ei	ΔK-increasing	SA533 B-1	Air	da/dN versus ΔKe
1 ec	ΔK-constant			
2ei	ΔK-increasing	SA533B-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 4 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
1 i	37	1980	1 c	92
2 i	68	1135	2 c	39
3 i	68	1991	3 c	94
4 i	36	1275	4 c	119
5 i	21	705	5 c	50

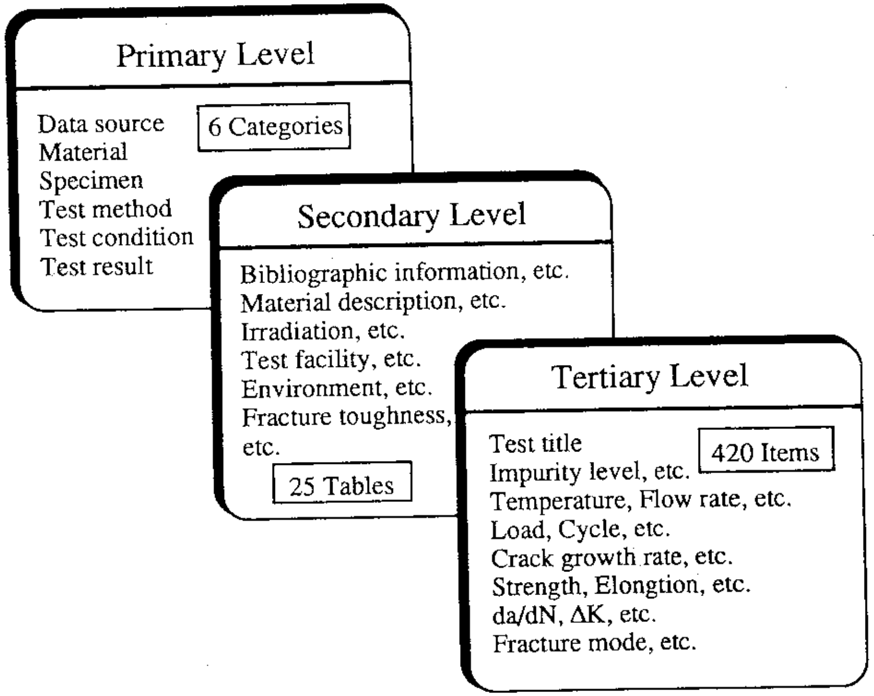


Fig. 1 Three-level hierarchy of data structure in the JMPD.

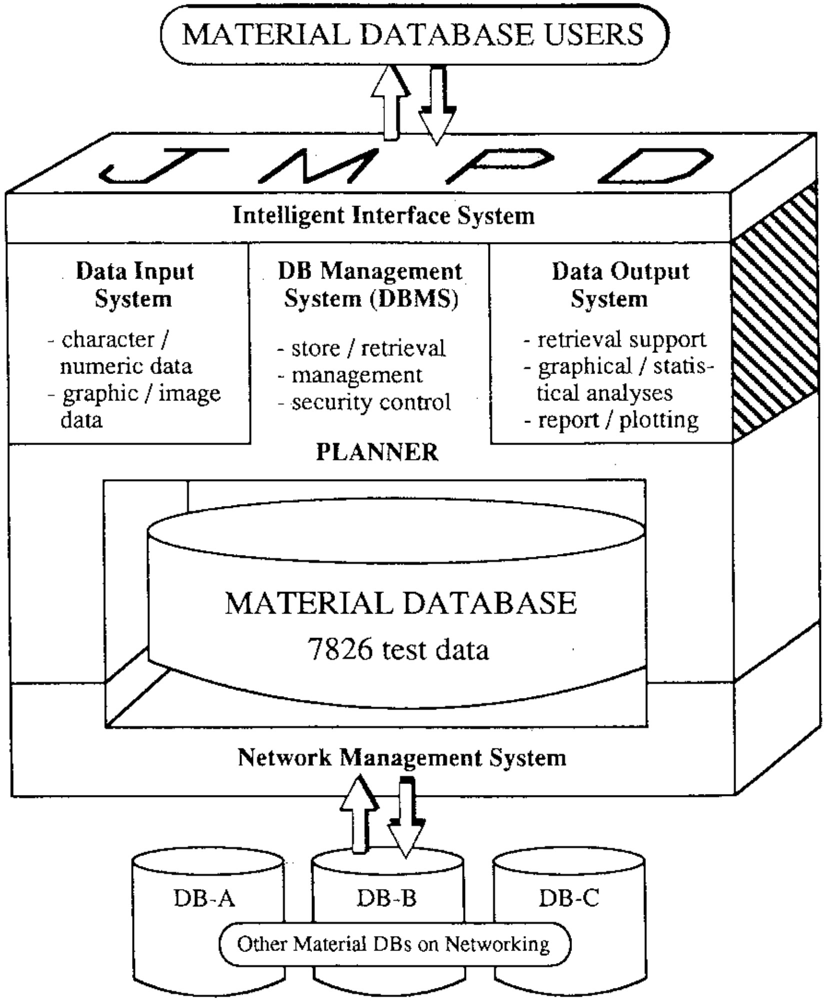
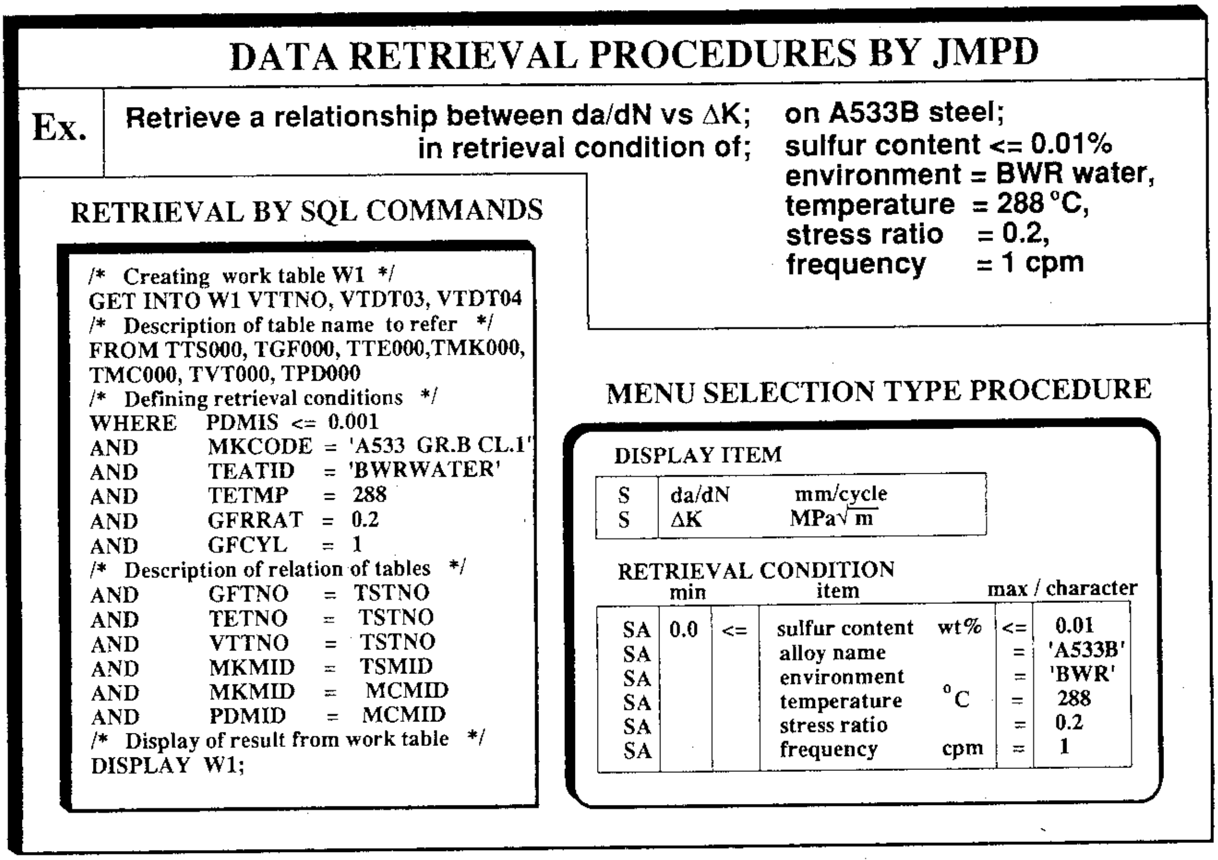


Fig. 2 Schematic concept of the JMPD.



DATA RETRIEVAL PROCEDURES BY JMPD

Ex. Retrieve a relationship between da/dN vs ΔK; on A533B steel;
in retrieval condition of; sulfur content <= 0.01%
environment = BWR water,
temperature = 288 °C,
stress ratio = 0.2,
frequency = 1 cpm

RETRIEVAL BY SQL COMMANDS

```
/*  Creating  work table W1  */
GET INTO W1 VTTNO, VTDT03, VTDT04
/*  Description of table name  to refer   */
FROM TTS000, TGF000, TTE000,TMK000,
TMC000, TVT000, TPD000
/*  Defining retrieval conditions   */
WHERE    PDMIS  <=  0.001
AND        MKCODE  =  'A533  GR.B CL.1'
AND        TEATID   =  'BWRWATER'
AND        TETMP    =  288
AND        GFRRAT  =  0.2
AND        GFCYL    =  1
/*  Description of relation of tables   */
AND        GFTNO    =  TSTNO
AND        TETNO    =   TSTNO
AND        VTTNO    =   TSTNO
AND        MKMID    =   TSMID
AND        MKMID    =    MCMID
AND        PDMID     =   MCMID
/*  Display of result from work table   */
DISPLAY  W1;
```

MENU SELECTION TYPE PROCEDURE

DISPLAY ITEM

S	da/dN	mm/cycle
S	ΔK	MPa$\sqrt{m}$

RETRIEVAL CONDITION

	min		item			max / character
SA	0.0	<=	sulfur content	wt%	<=	0.01
SA			alloy name		=	'A533B'
SA			environment		=	'BWR'
SA			temperature	°C	=	288
SA			stress ratio		=	0.2
SA			frequency	cpm	=	1

Fig. 3 Examples of data retrieval procedures by SQL commands and a menu screen.

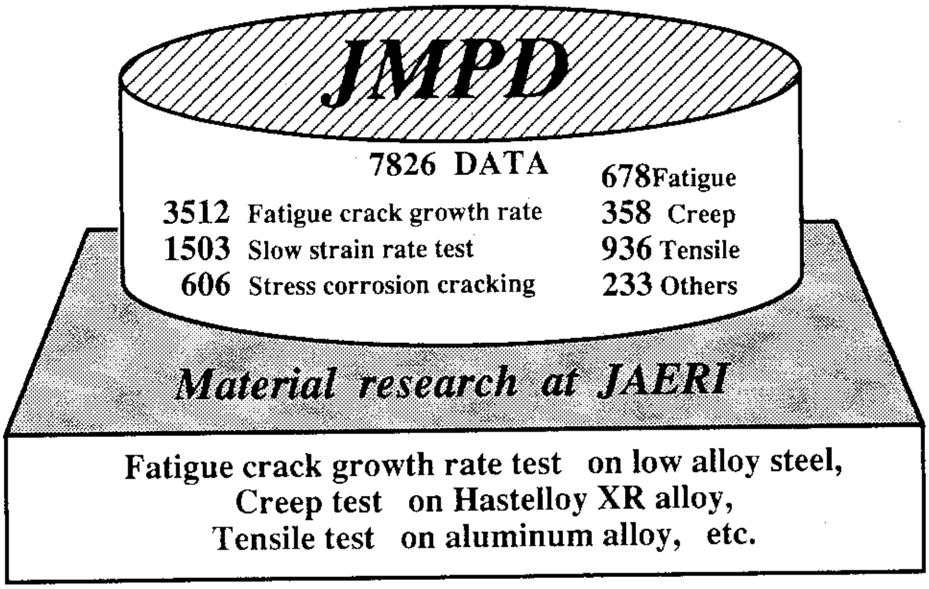


Fig. 4 Data stored in the JMPD based on the material research activities in JAERI.

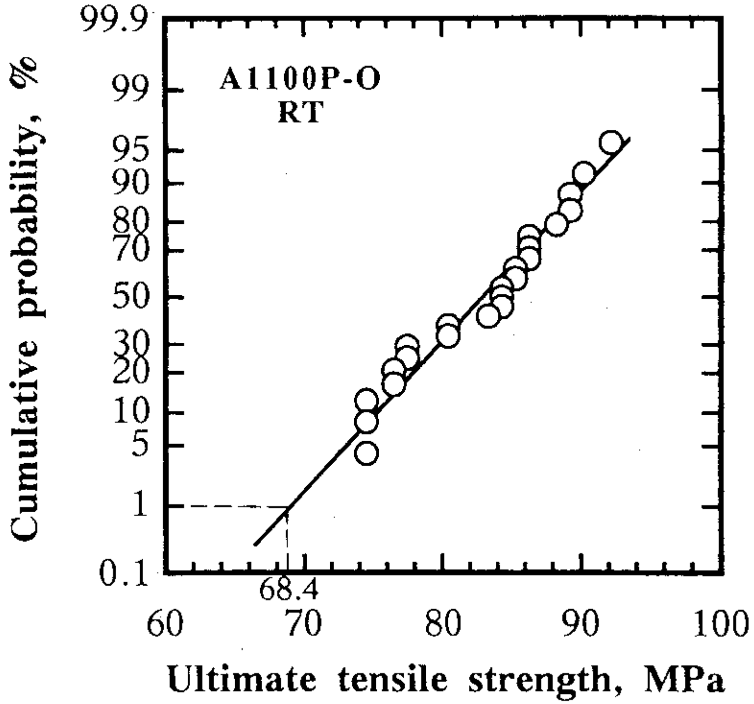


Fig. 5 Ultimate tensile strength plotted on normal probability paper for A1100P-O at RT.

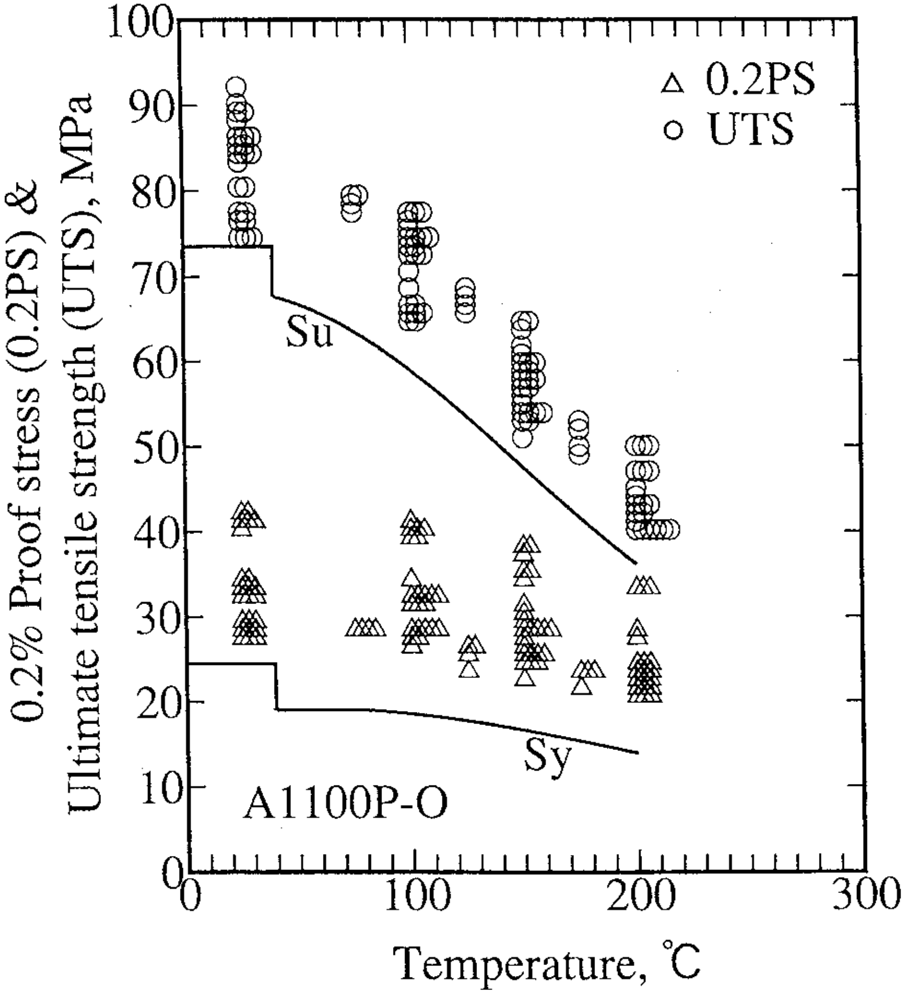


Fig. 6 0.2% proof stress, ultimate tensile strength and draft of Sy & Su for A1100P-O.

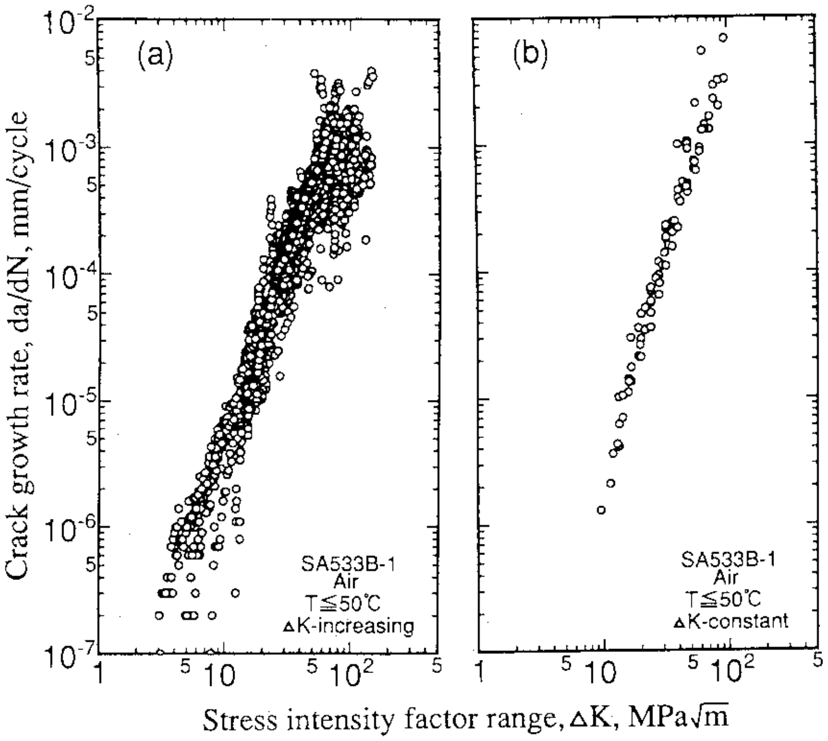


Fig. 7 Relation between da/dN and ΔK for SA533B-1 in air.
(a) ΔK-increasing type test, data set No.1i
(b) ΔK-constant type test, data set No.1c

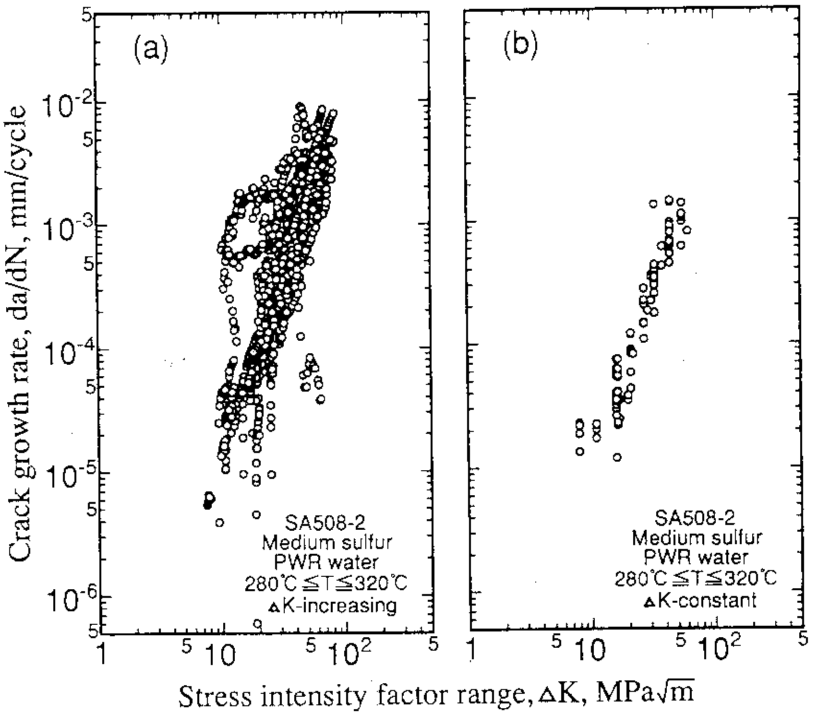


Fig. 8 Relation between da/dN and ΔK for SA508-2 with medium sulfur in simulated PWR primary coolant.
(a) ΔK-increasing type test, data set No.4i
(b) ΔK-constant type test, data set No.4c

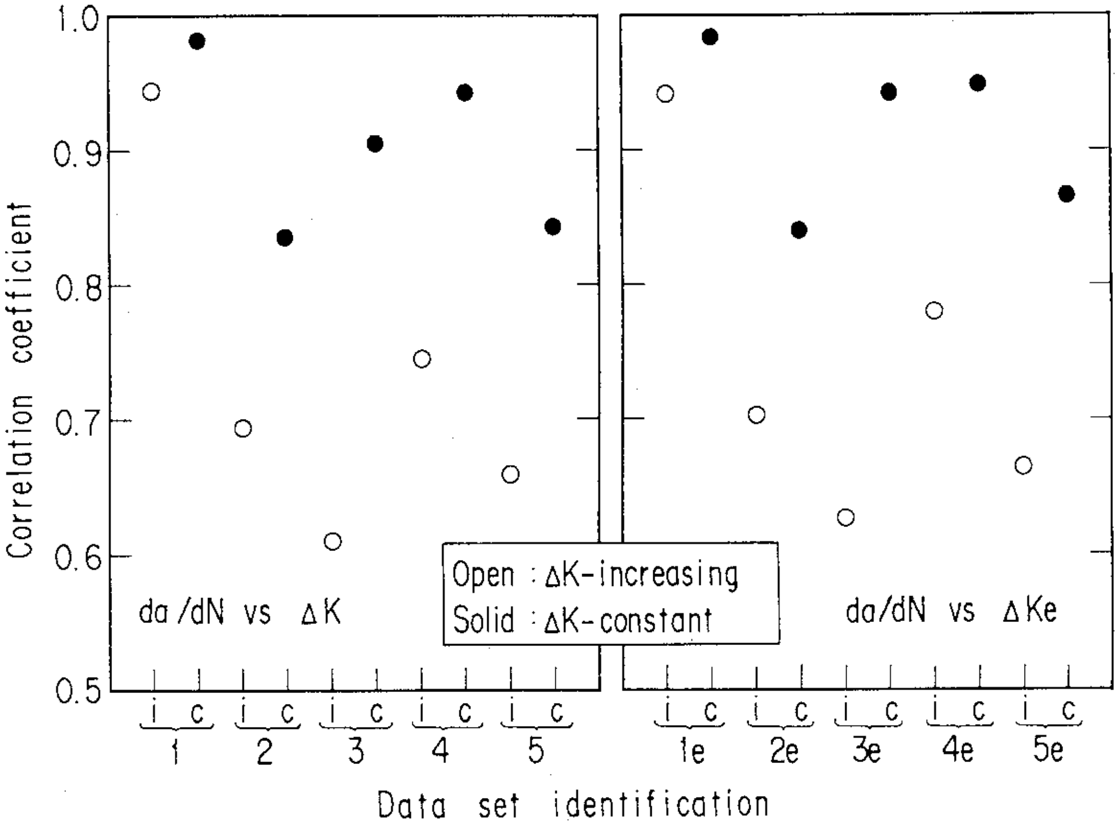


Fig. 9 Correlation coefficients for da/dN versus ΔK and/or da/dN versus ΔKe relations.

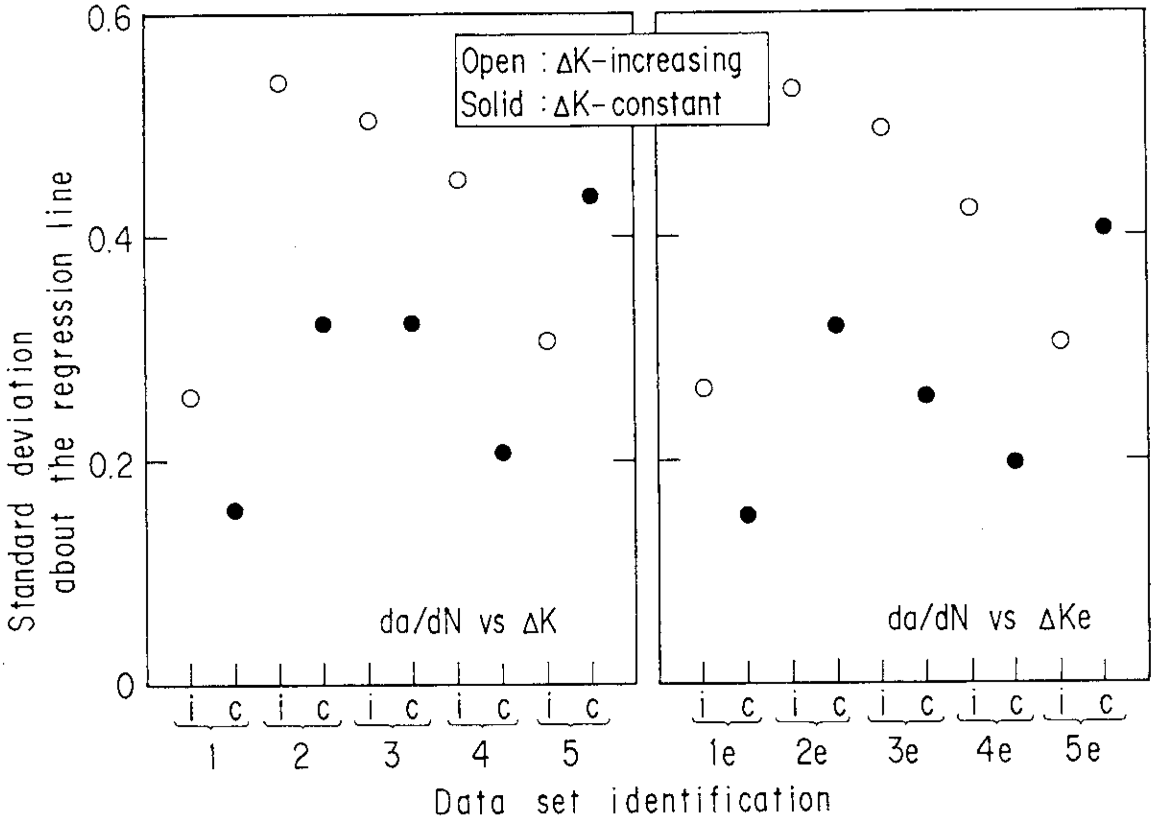


Fig. 10 Standard deviations about regression lines.

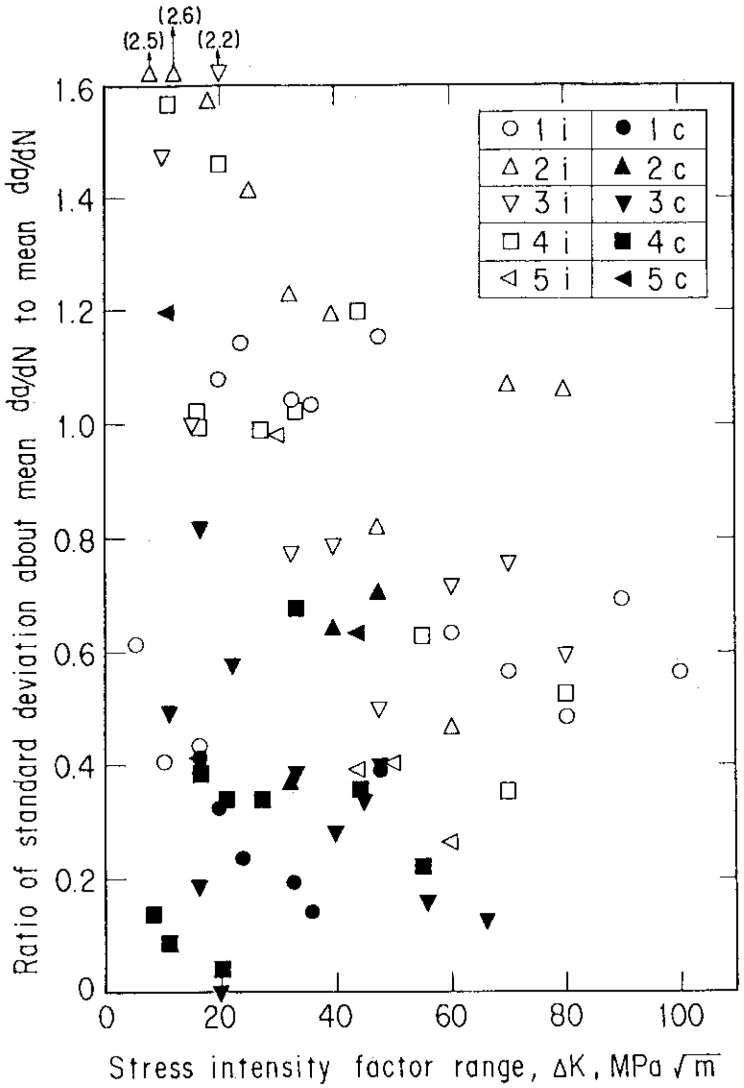


Fig. 11 Standard deviations about mean da/dN at several different ΔK levels for da/dN versus ΔK data.

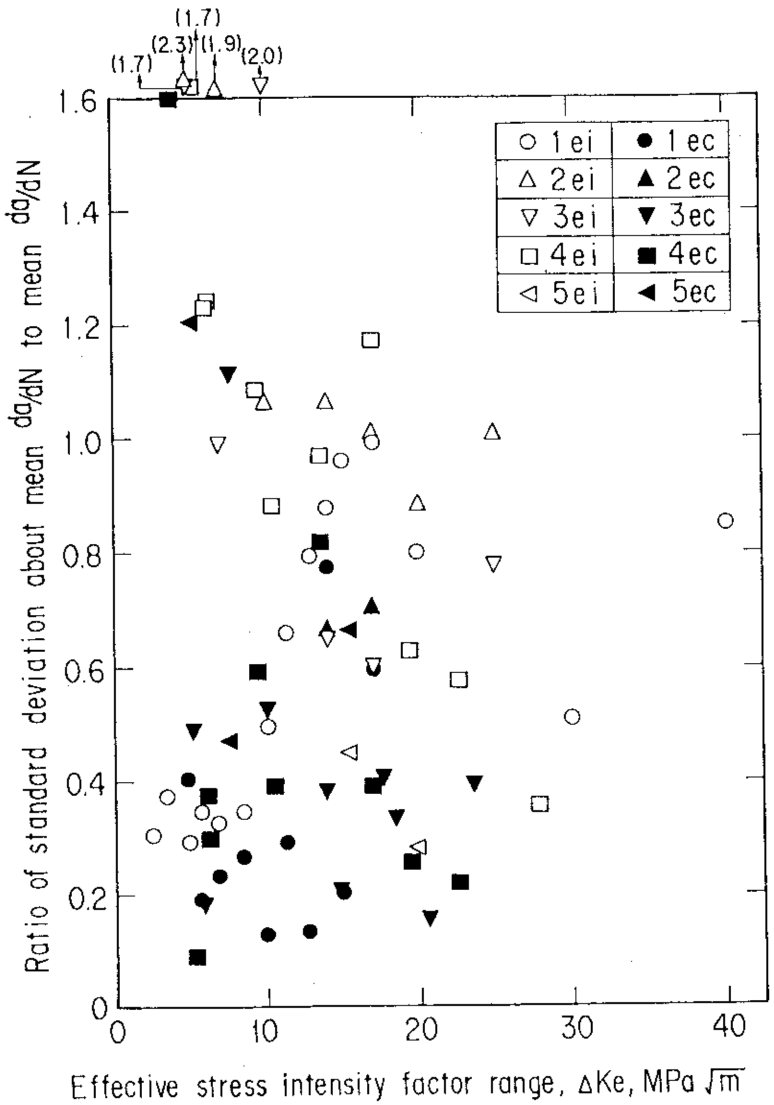


Fig. 12 Standard deviations about mean da/dN at several different ΔKe levels for da/dN versus ΔKe data.

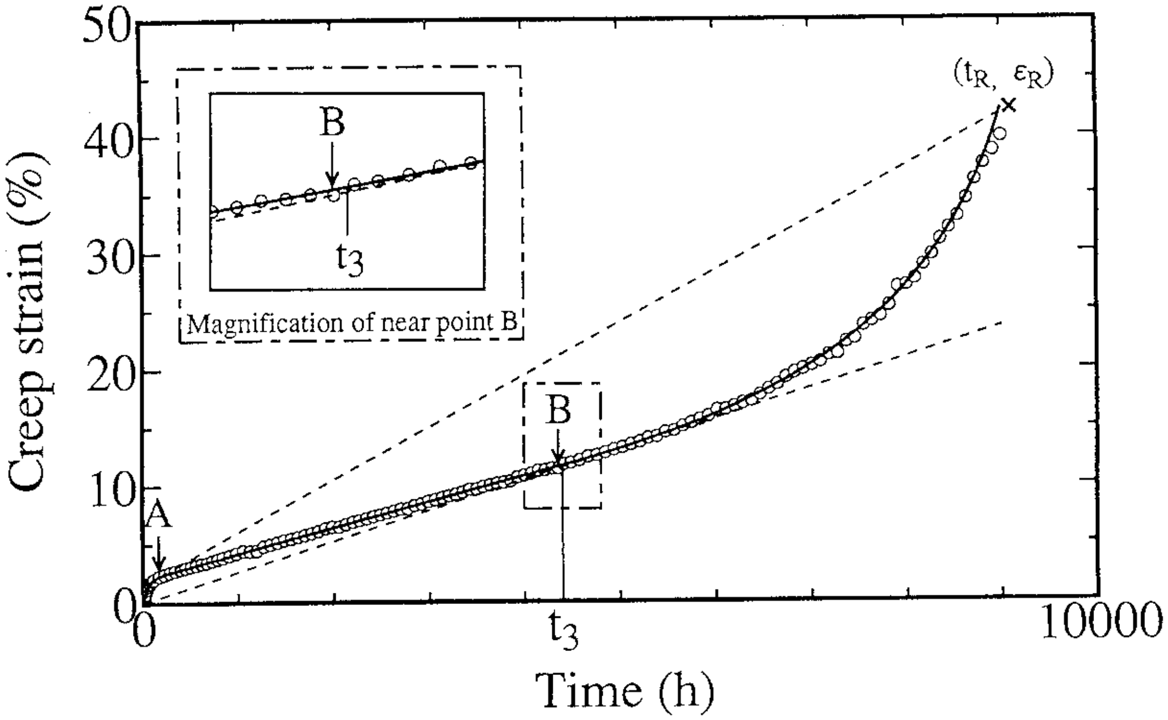


Fig.13 Schematic illustration of the method of determining the time to the onset of tertiary creep and the minimum creep rate. Points A and B give the minimum $(\varepsilon_R-\varepsilon)/(t_R-t)$ and the minimum ε/t, respectively. Cross indicates the rupture point.

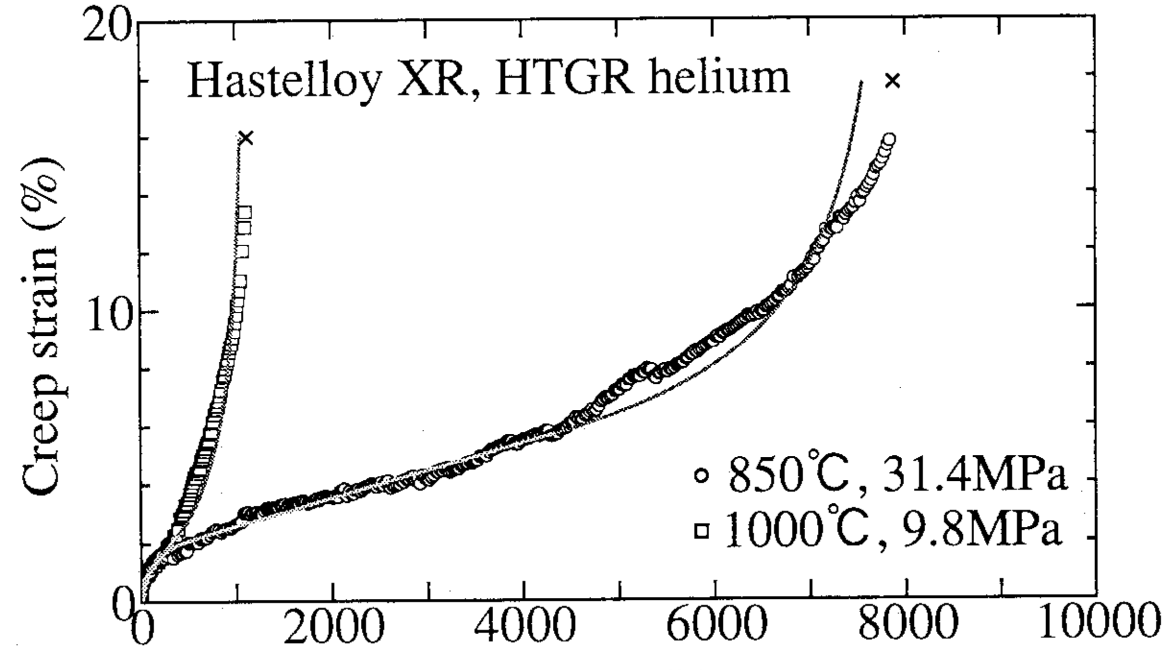


Fig.14 Example of creep curves on Hastelloy XR [33] and the result of evaluation by the proposed method. Crosses indicate the rupture points.