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# Fatigue Damage Management Based on Postulated Crack Growth Curve

Masayuki KAMAYA[1,*] and Takao NAKAMURA[2]

[1] Institute of Nuclear Safety System, Inc., 64 Sata, Mihama-cho, Fukui 919-1205, Japan
[2] Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan

## ABSTRACT

The postulated fatigue crack growth curve (P-curve), which represents the relationship between crack size and fatigue damage, has been developed for Type 316 stainless steel. In this study, further improvement of the P-curve was made. Particularly, the incubation period before initiation of a 0.1 mm depth crack was newly included in the P-curve. Then, the P-curve was extended for thermal fatigue loading, which is the main cause of fatigue damage in nuclear power plant components. The stress and strain gradient in the depth direction derived from thermal convection analysis was reasonably considered in the crack growth prediction. It was shown that the fatigue damage (*DF*) of a component could be quantified using the P-curve and crack size detected by inspection, or even if no crack is detected, possible *DF* could be estimated from the detectable crack size of the inspection technique. By incorporating the probability of detection (*POD*) of an inspection technique into the P-curve, the PD-curve, which is the relationship between the *DF* and *POD*, was developed. It was discussed that the PD-curve can be used to show the specifications of inspection techniques necessary for ensuring component integrity.

## KEYWORDS

*low-cycle fatigue*, *fatigue life*, *crack growth*, *equivalent stress intensity factor*, *probability of detection*

## ARTICLE INFORMATION

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## 1. Introduction

The usage factor (UF) is used not only for design of nuclear power plant components but also for assessing structural integrity of operating plants. The factual UF for operating plants is calculated using loading history actually experienced and stress amplitude estimated by analysis. Although the UF is controlled at less than unity in the design, the factual UF may exceed the critical value due to long term plant operation. The allowable number of cycles used for calculating the UF is given by the design fatigue curve (DFC) prescribed in design codes [1][2]. Since enough margin is considered in determining the DFC from test results, a component does not necessarily fail due to the fatigue damage even if the UF exceeds unity. Actually, to the authors' knowledge, no crack has been found in nuclear plant components for which fatigue damage was assessed in the design [3][4].

In order to control the fatigue damage of operating plants properly, it is important to know the actual fatigue damage accumulated in components. Since the fatigue damage is brought about by crack initiation and growth [5][6] and the failure mode brought about by fatigue damage is cracking, the magnitude of the fatigue damage can be represented by crack size. Previously, the authors proposed the concept of a postulated fatigue crack growth curve (hereafter, P-curve) which shows the relationship between the UF and crack size [7]. By using the P-curve, the actual fatigue damage accumulated in components can be estimated from the crack size identified by inspections [7]. Even if no crack is detected, possible damage can be estimated from the detectable crack size of the inspection technique applied.

This study was aimed at showing the procedure to quantify the fatigue damage accumulated in components and the specifications of inspection techniques required to ensure the component integrity. Low and high cycle fatigue of a Type 316 stainless steel was focused on. In the previously developed P-curve [7], the incubation period before the small crack initiation was not considered. In this study, first, the incubation period was considered in the P-curve for assessing the fatigue damage particularly

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[*] Corresponding author, E-mail: kamaya@inss.co.jp

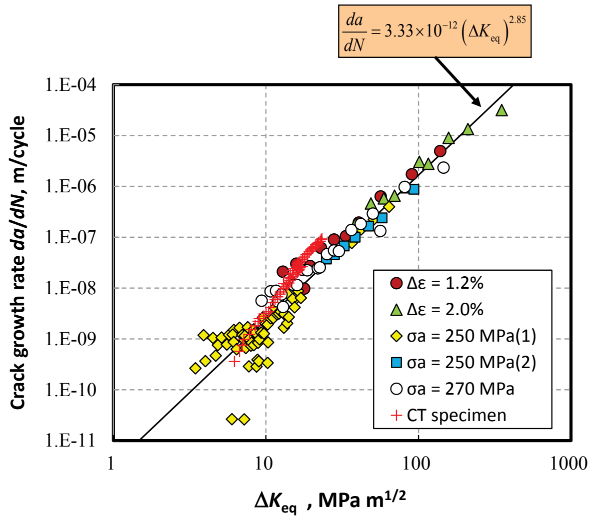


**Fig. 1 Fatigue crack growth rates obtained using cylindrical specimens together with replica investigations and CT specimens.**

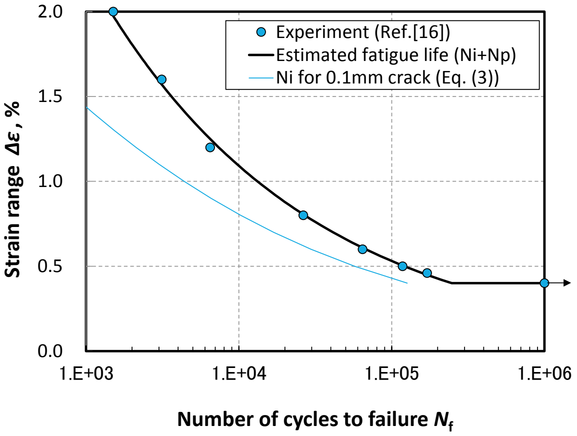


**Fig. 2 Incubation period before 0.1 mm crack initiation, fatigue life by low-cycle fatigue tests and estimated fatigue life.**

for the high-cycle regime. Then, the P-curve was extended to the crack growth under thermal fatigue, which is the main cause of fatigue damage in nuclear power plant components. Finally, the probability of detection of inspection technique was considered in the P-curve. It allowed specifications of inspection techniques necessary for ensuring the component integrity to be quantified.

## 2. Crack Growth Rate and Incubation Period for Developing Postulated Fatigue Crack Growth Curve (P-curve)

### 2.1 Crack growth prediction

In order to predict the crack growth not only for high-cycle fatigue regime but also for the low-cycle fatigue regime, the growth rate for a given strain range has to be quantified. Then, the growth rate prediction model for strain range was discussed in this section. Crack growth rates have been obtained for Type 316 stainless steel [8][9]. Initiation and growth of small cracks less than tens of micrometers in length could be captured by periodical replica investigations made for round-bar specimens subjected to strain or stress controlled fatigue tests. Figure 1 shows the relationship between the crack growth rates obtained and the equivalent strain intensity factor ($\Delta K_{\mathrm{eq}}$) [8][10], which is defined by:

$$\Delta K_{\mathrm{eq}} = f\,\Delta\varepsilon E\sqrt{\pi a} \tag{1}$$

where $\Delta\varepsilon$ is the applied strain range, $a$ is the crack depth, $f$ is the geometrical constant for the stress intensity factor, and $E$ is Young's modulus at room temperature ($E$ = 195 GPa). The growth rates obtained using a compact tension (CT) specimens under the small scale yielding condition are also shown in the figure. The measured crack growth rates correlated well with $\Delta K_{\mathrm{eq}}$ regardless of the loading amplitude and yielding condition [11][12]. It should be noted that significant scattering was found when the stress intensity factor was used for the abscissa of Fig. 1 [8].

Regression of the growth rates obtained using round-bar specimens was derived as [9]:

$$\frac{da}{dN} = 3.33\times10^{-12}\left(\Delta K_{\mathrm{eq}}\right)^{2.85} \tag{2}$$

where the growth rate is given in m/cycle and $\Delta K_{\mathrm{eq}}$ in MPa $\mathrm{m}^{0.5}$. The fatigue life of stainless steel correlated well with the strain range rather than the stress range [13][14]. It was shown that fatigue lives of work hardened stainless steel were almost the same as those of annealed stainless steel under

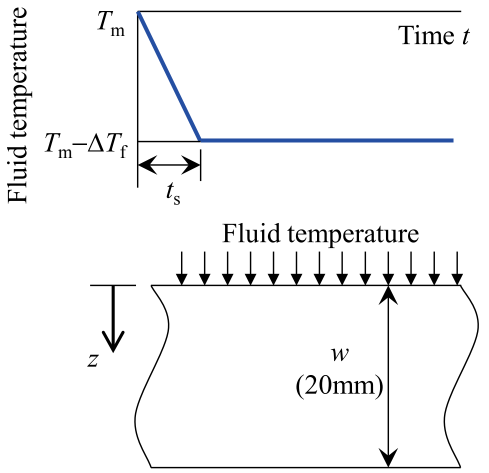


**Fig. 3 Analyzed model for thermal fatigue caused by fluid temperature change.**

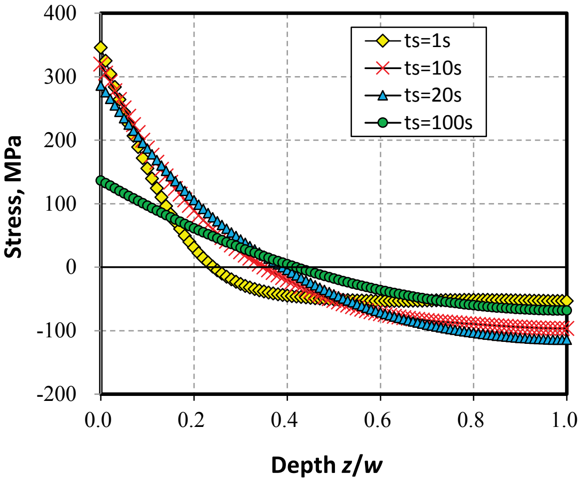


**Fig. 4 Stress distribution in the thickness direction obtained for $\Delta T_f = 100$K.**

the same strain range despite the stress amplitude of the hardened material being much higher [15]. This implied that the stress amplitude and maximum stress had little influence on fatigue life and fatigue life can be predicted from the strain range. Since low-cycle fatigue life is almost equivalent to the cycles for crack growing [8], it is important to predict the crack growth for a given strain range in order to correlate the crack growth prediction to the fatigue life. The equivalent strain intensity factor together with Eq. (2) enables the crack growth for a given strain range to be predicted without considering the stress amplitude.

### 2.2 Determination of incubation period

In order to conduct the crack growth prediction, it is necessary to determine the initial crack depth for calculating $\Delta K_{eq}$. In this study, the initial crack depth for growth prediction was assumed to be 0.1 mm. Then, the incubation period before the crack initiation, which is denoted as $N_i$, was determined so that the sum of $N_i$ and the cycles necessary for the crack growth to 3 mm in depth was identical to the fatigue life obtained by the strain-controlled tests [16]. The regression of the evaluated $N_i$ was obtained as:

$$N_i = 3948\left(\Delta\varepsilon[\%]\right)^{-3.95}. \tag{3}$$

Fig. 2 shows the $N_i$ given by Eq. (3), predicted fatigue lives and the test results. The prediction using Eqs. (2) and (3) could successfully estimate the fatigue life by the tests.

The change in crack depth with the number of cycles normalized by the fatigue life $N/N_f$, which is referred to as fatigue damage and denoted as $DF$, is shown in Fig. 2 for various strain ranges. The curves shown in Fig. 2 correspond to the P-curves.

## 3. P-curve for Thermal Stress

Most of the fatigue damage considered in component design of nuclear power plants is brought about by thermal transients due to changes in operating modes. The cyclic stress and strain caused by the fluid temperature fluctuation on a component surface forms a gradient in the depth direction. For instance, the stress fluctuation has its maximum value at the surface and this becomes smaller in the depth direction. The conventional fatigue damage assessment using the DFC only considers the maximum stress at the surface. On the other hand, it is possible to take retardation in the crack growth due to the gradient into account in the crack growth prediction.

Stress response to ramp change of fluid temperature was considered in this study. The

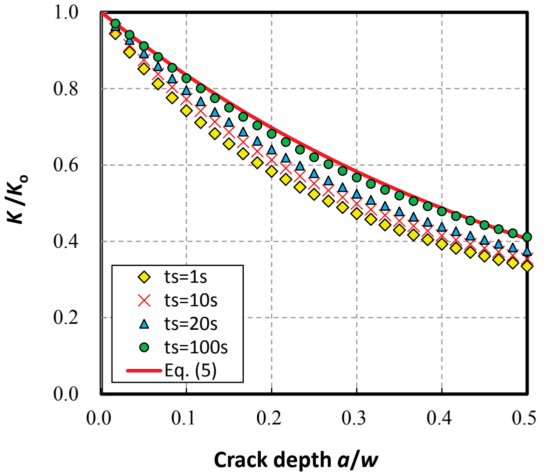


**Fig. 5 Change in normalized stress intensity factor with crack depth under various rise times $t_s$.**

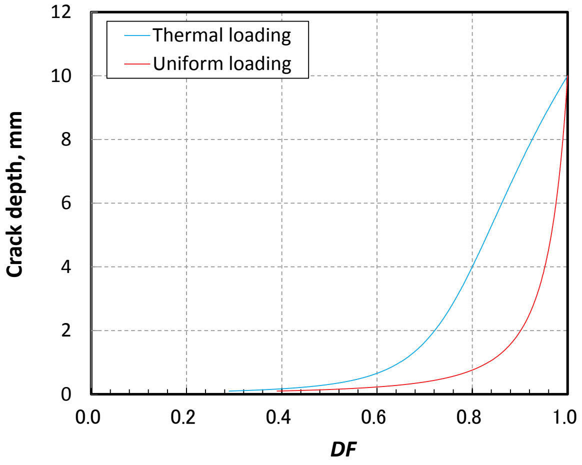


**Fig. 6 Crack initiation and growth prediction made using Eqs. (2) and (3) (P-curve).**

temperature was assumed to be changed from $T_m$ to $T_m$–$\Delta T_f$ with a transient time of $t_s$ as shown in Fig. 3. By solving this thermal convection problem assuming the plate thickness $w$ = 20 mm, $\Delta T_f$ = 100 K and constants for stainless steel [17], the thermal stress distribution when the stress at the surface becomes a maximum could be obtained as Fig. 4 [18]. Then, the stress intensity factor (SIF) was derived using weight function [19] as shown in Fig. 5. The SIF was normalized by $K_o$ obtained by:

$$K_o = f\sigma_{\max(z=0)}\sqrt{\pi a}\,. \tag{4}$$

Here $\sigma_{\max(z=0)}$ denotes the maximum stress at the surface. Although the smaller $t_s$ caused larger $\sigma_{\max(z=0)}$ as shown in Fig. 4, $K/K_o$ exhibited almost the same change with $a/w$ regardless of $t_s$. It should be noted that the change in $K/K_o$ was also insensitive to the heat transfer coefficients between the fluid and the plate. The change in $K/K_o$ with crack depth was approximated by:

$$\frac{K}{K_o} = \exp\left(\frac{-1.8a}{w}\right). \tag{5}$$

Since $\sigma_{\max(z=0)}$ has been calculated for obtaining UF, it is possible to predicted crack growth under the thermal stress without difficulty. Crack initiation and growth prediction was made for the uniform and thermal stress conditions and results are plotted in Fig. 6 ($\Delta\varepsilon$ = 0.8%). The incubation period of 0.1 mm depth crack was determined by Eq. (3) and growth prediction was made using Eq. (2). The fatigue life was determined when the depth reached 10 mm. The equivalent stress intensity factor for thermal stress was calculated from Eqs. (4) and (5) by replacing $K$ with $\Delta K_{eq}$ and $\sigma_{\max(z=0)}$ with $E\Delta\varepsilon$. The number of cycles was represented by the *DF*. Fig. 6 corresponds to the P-curve for thermal fatigue.

## 4. Application of P-curve to Plant Maintenance

### 4.1 Development of PD-curve for maintenance

By using the P-curve shown in Fig. 6, it is possible to estimate the fatigue damage accumulated in components from the size of a detected crack. Flaw detectability of an inspection technique is represented by *POD* (Probability Of Detection). In general, the detectability increases as the crack size becomes larger and the maximum value is unity. By combining the POD curve (*POD* vs. *a*) and P-curve (*a* vs. *DF*), the relationship between *POD* and *DF*, which is referred to as the PD-curve, is obtained as schematically shown in Fig. 7. The PD-curve tells that, for the case shown in Fig.7, the maximum *DF* was less than 0.7 if no crack was found by the inspection. In other words, the remaining fatigue life was more than 30% of the total fatigue life. Improvement of the inspection technique can extend the residual fatigue life ensured by the inspection. Since most inspections made for power plants do not detect cracks, it is important to feed back the information that there are no cracks to plan future maintenance tasks.

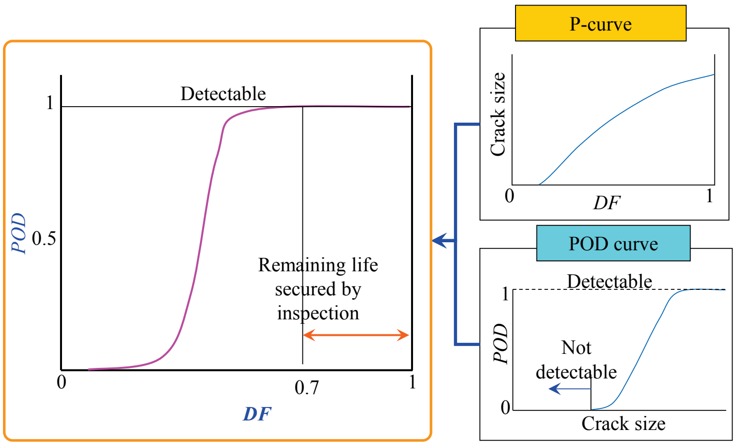


**Fig. 7 Schematic drawing representing PD-curve development procedure using the P-curve and POD curve.**

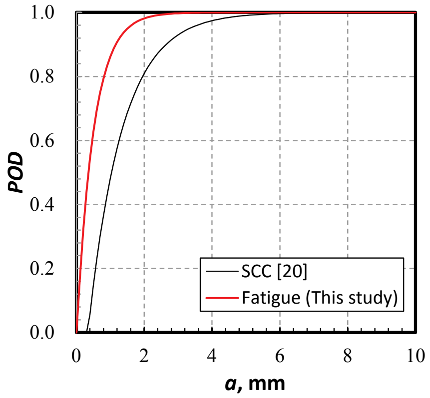
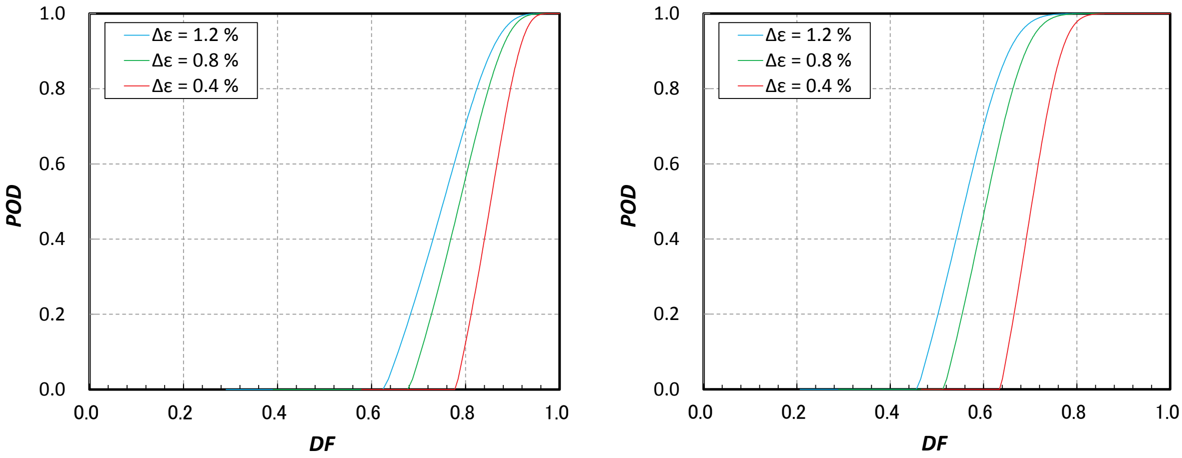


**Fig. 8 POD curve assumed for the analyses and one from the literature [20].**



**(a) Cyclic uniform stress** **(b) Cyclic thermal stress**

**Fig. 9 PD-curves determined for fatigue crack initiation and growth of Type 316 stainless steel under cyclic uniform and thermal**

## 4.2 PD-curve for thermal stress

In this study, the *POD* was assumed as:

$$POD = 1 - \exp\left\{\alpha\left(0.3434 - a\right)\right\}. \qquad (6)$$

Eq. (6) was derived from ref. [20], which was determined for stress corrosion cracking (SCC). Although $\alpha = 1$ for SCC, $\alpha = 2$ was assumed in this study for fatigue cracking as shown in Fig. 8. By combining the POD curve ($a$ vs. *POD*) and P-curve, the PD-curve could be derived as shown in Fig. 9.

The PD-curve depends on $\Delta\varepsilon$. It is worth mentioning that the PD-curves (and also the P-curves) obtained for different $\Delta\varepsilon$ values become identical if the $N_{\mathrm{i}}$ does not depend on $\Delta\varepsilon$. The PD-curves for cyclic thermal stress shown in Fig. 9(b) indicate that cracks can be detected by inspection when the fatigue damage was more than 70-80%. On the other hand, for the uniform stress condition (Fig. 9(a)) such as cyclic internal pressure, cracks are difficult to find because they can be found only when *DF* becomes more than 0.9. This implies that the inspection interval should be less than 0.1*DF* in order to detect a crack before it causes failure. This is the case for the inspection techniques with *POD* given by Eq. (6) ($\alpha = 2$). Improvement of the *POD* permits detection of a crack at smaller *DF*.

## 5. Discussion

By using the PD-curve, it is possible to define the specifications of inspection techniques required. This allows maintenance activities to be improved. For example, the following benefits can be realized.

(1) Frequency of inspection can be reduced by improving *POD*.
(2) Cost effectiveness can be optimized by controlling the frequency of inspection, inspection technique applied, level of inspector and so on.
(3) Allowable crack size depends on the component and position of the fatigue crack. Larger cracks may be allowed for larger components. This effect can be considered in the fatigue damage assessment using the PD-curve.
(4) If the risk assessment is included in the inspection program, detection of every crack is not always required. The possibility of a failed detection can be included in the risk assessment.

It has been thought that a higher *POD* is preferred for component integrity and the inspection technique has been improved continuously. However, no goal for the *POD* was set and the flaw acceptance standard [21] was used. This means that current inspection techniques may be set at an excessively high level or, on the contrary, the *POD* may not be sufficient to secure the integrity. The PD-curve makes it possible to quantify the inspection specifications required.

Most of the inspections made for actual plants do not detect flaws. Therefore, the result “no crack is found” is as important as detecting cracks. The result of “no crack” can be reflected to planning future inspection tasks by using the PD-curve. As mentioned above, the current *DF* can be deduced using the result of “no crack” from the P-curve or PD-curve.

## 6. Conclusion

In this study, the P-curve for Type 316 stainless steel was improved in order to quantify the fatigue damage accumulated in components and to specify inspection techniques required to ensure the component integrity. The incubation period before initiation of a 0.1 mm depth crack was considered in the P-curve, and then, the P-curve was extended to include crack growth under thermal fatigue, which is the main cause of fatigue damage of nuclear power plant components. It was shown that the P-curve allowed the fatigue damage (*DF*) to be quantified using the crack size detected by inspection or to be estimated from the detectable crack size of the inspection techniques if no crack is detected. The PD-curve was developed by incorporating the *POD* of the inspection techniques into the P-curve. It was shown that the PD-curve can be used to show the specifications of inspection techniques necessary for ensuring the component integrity.

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## References

[1] ASME, “Rules for Construction of Nuclear Facility Components – ASME Boiler and Pressure Vessel Code Section III”, ASME, New York (2013).
[2] Japan Society Mechanical Engineers, “Codes for Nuclear Power Generation Facilities: Rules on Design and Construction for Nuclear Power Plants”, JSME S NC1-2012 (2012).
[3] T. Metais, E. Karabaki, L. De Baglion, J. Solin, J. Le Roux, S. Reese, S. Courtin, “European contributions

to environmental fatigue issues experimental research in France, Germany and Finland", Proceedings of the ASME 2014 Pressure Vessels and Piping Conference, Anaheim, CA, USA, July, paper no. 28207 (2014).

[4] M. Walter, T. Gilman, K. Evon, "Fatigue life of BWR feedwater nozzles considering actual plant transients", Proceedings of the ASME 2014 Pressure Vessels and Piping Conference, Anaheim, CA, USA, July, paper no. 28891 (2014).

[5] Y. Murakami, K. J. Miller, "What is fatigue damage? A view point from the observation of low cycle fatigue process", International Journal of Fatigue, Vol. 27, pp. 991-1005 (2005).

[6] Y. Xue, "Modeling fatigue small-crack growth with confidence – A multistage approach", International Journal of Fatigue, Vol. 32, pp. 1210-1219 (2010).

[7] M. Kamaya, T. Nakamura, "A flaw tolerance concept for plant maintenance using virtual fatigue crack growth curve", Proceedings of the ASME 2013 Pressure Vessels and Piping Conference, Paris, France, July, paper no. 97851 (2013).

[8] M. Kamaya, M. Kawakubo, "Strain-based modeling of fatigue crack growth – An experimental approach for stainless steel", International Journal of Fatigue, Vol. 44 pp. 131-140 (2012).

[9] M. Kamaya, M. Kawakubo, "Damage assessment of low-cycle fatigue by crack growth prediction (development of growth prediction model and its application)", Transactions of the Japan Society of Mechanical Engineers Ser. A, Vol. 78 pp. 1518-1533 (2012).

[10] J. R. Haigh, R. P. Skelton, "A strain intensity approach to high temperature fatigue crack growth and failure", Materials Science and Engineering, Vol. 36, pp.133-137 (1978).

[11] H. Kitagawa, S. Takahashi, C.M. Suh, S. Miyashita, "Quantitative analysis of fatigue process - microcracks and slip lines under cyclic strains", ASTM STP 675, pp.420-449 (1979).

[12] M. Kamaya, "Low-cycle fatigue crack growth prediction by strain intensity factor", International Journal of Fatigue, in press.

[13] C. E. Jaske, W. J. O'Donnell, "Fatigue design criteria for pressure vessel alloys", ASME Journal of Pressure Vessel Technology, Vol. 99, pp.584-592 (1977).

[14] J. Colin, A. Fatemi, "Variable amplitude cyclic deformation and fatigue behavior of stainless steel 304L including step, periodic, and random loading", Fatigue & Fracture of Engineering Materials & Structures, Vol. 33, pp.205-220 (2010).

[15] M. Kamaya, M. Kawakubo, "Mean stress effect on fatigue strength of stainless steel", International Journal of Fatigue, in press.

[16] M. Kawakubo, M. Kamaya, "Fatigue life prediction of stainless steel under variable loading (damage factors determining fatigue life and damage evaluation for two-step test)", Journal of the Society of Materials Science, Japan, Vol. 60, pp.871-878 (2011).

[17] M. Kamaya, "Assessment of thermal fatigue damage caused by local fluid temperature fluctuation (Part I: Characteristics of constraint and stress caused by thermal striation and stratification)", Nuclear Engineering and Design, Vol. 268, pp.121-138 (2014).

[18] M. Kamaya, "Damage assessment of low-cycle fatigue by crack growth prediction (fatigue life under cyclic thermal stress)", Transactions of the Japan Society of Mechanical Engineers Ser. A, Vol. 79, pp.1530-1544 (2013).

[19] M. Kamaya, "Assessment of thermal fatigue damage caused by local fluid temperature fluctuation (Part II: Crack growth under thermal stress)", Nuclear Engineering and Design, Vol. 268, pp.139-150 (2014).

[20] H. Machida, "Influence of non-destructive examination performance on reliability of pipes having stress corrosion cracks", Transactions of the Japan Society of Mechanical Engineers Ser. A, Vol. 77, pp.1798-1813 (2011).

[21] Japan Society Mechanical Engineers, "Codes for Nuclear Power Generation Facilities: Rules of Fitness-for-Service for Nuclear Power Plants", JSME S NA1-2012 (2012).