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Low-cycle fatigue crack growth prediction by strain intensity factor

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ABSTRACT

The validity of the strain intensity factor for representing driving force of fatigue crack growth under the large scale yielding condition was shown in this study. First, a crack growth test technique using plate specimens was developed in order to apply a fully-reversed cyclic load and to measure the global strain for calculating the strain intensity factor. Fatigue crack growth tests using Type 316 stainless steel revealed that the growth rates correlated well with the strain and effective strain intensity factor ranges for various stress or strain ranges, specimen geometries and loading modes (stress- and strain-controlled). Based on the test results, validity and physical meaning of the strain intensity factor were discussed. It was concluded that the strain intensity factor was an effective parameter for predicting crack growth under the small and large scale yielding conditions.

1. Introduction

Extensive attempts have been made to estimate the number of cycles to specimen failure (hereafter, fatigue life) by predicting fatigue crack initiation and growth [1–6]. The fatigue life can be divided into two phases: the number of cycles to small crack initiation and the number of cycles for the initiated crack growth to a critical size for specimen failure. The periodical replica investigations made for cylindrical specimens of Type 316 stainless steel [7,8] revealed that the number of cycles before initiating a small crack of several tens of micrometers in length was less than 10% of the total fatigue life. Therefore, the fatigue life can be estimated by predicting the crack growth [9–11]. The growth prediction enables the relationship to be drawn between the crack size and number of cycles normalized by the fatigue life, which is referred to as the fatigue damage in this study. The relationship allows estimation of the fatigue damage of actual components by measuring the size of cracks initiated in components [12]. Even if no crack is found by an inspection, it is possible to say that the crack size (fatigue damage) is less than the detectable size of the inspection technique applied [12].

The stress intensity factor (SIF) is generally used for predicting the fatigue crack growth together with the well-known empirical crack growth model, known as the Paris law [13]. The ASTM standard [14] specifies test procedures for obtaining the relationship between the SIF and crack growth rates using pre-cracked specimens such as a compact tension specimen. In order to validate the SIF for the test specimen, the applied load and crack or specimen size are controlled so that the small scale yielding condition is preserved.

On the other hand, the fatigue life is basically investigated using cylindrical specimens under a fully-reversed cyclic axial loading condition. For stainless steels, since the fatigue limit is comparable to the proof strength of materials [15], cyclic plastic strain is observed during the fatigue tests [16]. Therefore, the small scale yielding condition is difficult to satisfy near the crack tip initiated during the fatigue test. It has been shown that the fatigue life of stainless steels correlates better with the strain range than with the stress amplitude even in the high-cycle fatigue regime [17,18]. For example, fatigue lives of cold worked stainless steels were almost the same as those of non-cold worked stainless steel for the same strain range [19–23]. Although the cold working increased the stress amplitude for a given strain range, the altered stress amplitude had little influence on the fatigue life. In actual practice, the fatigue life assessment for designing power plant components is performed using the strain-based design fatigue curve [24–27].

Since the fatigue life correlates well with the strain range and the fatigue life corresponds to the number of cycles for a crack growing to the critical size, the crack growth prediction should be made not by the SIF but by a parameter derived using strain range. It has been shown that the *J*-integral value correlated well with the growth rate obtained under the large scale yielding condition [28–31]. However, the *J*-integral value is derived using not only the strain but also the stress. Therefore, the fatigue life

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estimated using the J-integral value depends on the stress amplitude, although the stress amplitude had little influence on the fatigue life [19–23]. On the other hand, the range of the strain intensity factor ΔK_ε is defined by:

$$\Delta K_\varepsilon = f \Delta\varepsilon \sqrt{\pi a} \tag{1}$$

where f is the geometrical constant and $f = 1$ has been used previously [32]. a denotes the crack size. The strain intensity factor range does not depend on the stress amplitude. Several studies [33–36] showed that the strain intensity factor range correlated well with the fatigue crack growth rates for various materials even under the large scale yielding condition. The use of the strain intensity factor range for predicting the crack growth allows estimation of the fatigue life for a given strain range. It was shown that the predicted fatigue life corresponded well with that obtained by the low-cycle fatigue test using cylindrical specimens [16].

Despite the relevance of the strain intensity factor range for crack growth prediction, it is not generally used. One possible reason is that the physical meaning of the strain intensity factor is not clear [16]. The SIF is the mechanical parameter representing the magnitude of stress singularity near the crack tip. However, it is difficult to say the strain intensity factor represents the strain singularity at the crack tip under the large scale yielding condition. Since $\Delta\varepsilon$ and $\Delta\sigma$ have a linear correlation for an elastic condition, the geometrical constant f used for the SIF can be used for the strain intensity factor for the small scale yielding condition. However, it has not been shown whether the same f can be used for the large scale yielding condition. The testing procedure to obtain the crack growth rates is another problem for quoting the strain intensity factor range. It is difficult to specify $\Delta\varepsilon$ for compact tension specimens. Furthermore, testing fixtures for crack growth investigation generally require the minimum load to be more than zero, while compressive load has to be applied to simulate cyclic plastic strain observed in the fatigue tests using cylindrical specimens.

This study was aimed at developing a crack growth test technique for the large scale yielding condition and showing the validity of the strain intensity factor range for predicting the crack growth. First, a crack growth test technique using a plate specimen was developed. The single edged and round notched plate specimens were designed and the compliances for crack length monitoring were obtained by finite element analysis (FEA). The use of the plate specimen allows specification of the strain range for calculating the strain intensity factor. Then, Type 316 stainless steel was subjected to the fatigue crack growth tests. The correlation between the crack growth rates and strain intensity factor range was obtained under various loading conditions. The growth test using the round notched plate specimen was conducted to show the validity of the strain intensity factor range for predicting the crack growth from a notch root. Based on the test results, finally, the physical meaning of the strain intensity factor was discussed.

2. Development of crack growth test technique

2.1. Specimen geometries

The geometries of specimens used for crack growth tests are shown in Fig. 1. Smooth and notched specimens were used for crack growth tests. The specimens had a rectangular cross section with a thickness and width of 6 mm and 15 mm, respectively. The smooth specimen had a 36 mm long parallel section in order to specify the global strain. The round notch of 7.5 mm radius was introduced into the notched specimen. Edges for attaching a clip gage were machined at the longitudinal center of the specimen and a 0.5 mm long pre-crack was introduced using an electron discharge machine.

2.2. Testing protocol

The plate specimens were subjected to stress- or strain-controlled fully-reversed cyclic loading. In the strain-controlled test, the strain range measured by an extensometer attached at the back face was controlled so that it kept the objective value. The extensometer had a relatively large gage length, 25 mm, in order to reduce the influence of crack mouth opening on strain measurement. The strain was also measured by a strain gage attached 14 mm away from the pre-crack as shown in Fig. 2. The strain range measured by the strain gage was referred to as the global strain and used for $\Delta\varepsilon$ in Eq. (1) to calculate the strain intensity factor range.

The crack length during the fatigue test was monitored by the compliance method using a clip gage attached at the crack mouth as shown in Fig. 2. The relationship between the applied load and the crack mouth opening displacement measured by the clip gage allowed not only the crack length but also the crack mouth opening point to be identified

2.3. Elastic response of plate specimens

In order to develop a compliance function for crack length monitoring and to clarify the stress state of the notched specimen, elastic FEAs were carried out using the general-purpose finite element program Abaqus, Version 6.12. Fig. 3 shows the finite element meshes for the specimens. The 8-node isoparametric quadratic solid elements were used. Due to the symmetries of the problem, only one quarter of the plate was modeled by finite elements.

Fig. 4 shows the change in compliance with the normalized crack depth a/W, where a and W are the crack length and plate width, respectively. The crack depth was altered by changing the boundary condition at the symmetry plane. The normalized crack mouth opening displacement U was calculated using the displacement measured by the clip gage V and applied load P by:

$$U = \frac{1}{\sqrt{\frac{EtV}{P}} + 1} \tag{2}$$

where E and t are the Young's modulus and plate thickness, respectively. Then, by the root mean square method, the relationships between U and a/W were obtained as the following.

$$\frac{a}{W} = 3.2024 - 26.838U + 126.69U^2 - 342.28U^3 + 475.5U^4 - 263.28U^5 \text{ (Smooth specimen)} \tag{3}$$

$$\frac{a}{W} = -3.5629 + 62.49U - 305.64U^2 + 658.59U^3 - 655.7U^4 + 239.9U^5 \text{ (Notched specimen)} \tag{4}$$

The constant f for the stress and strain intensity factors was calculated by Eq. (5) for the smooth specimen [37]

$$f = 0.265\left(1 - \frac{a}{W}\right)^4 + \left(0.857 + 0.265\frac{a}{W}\right)\left(1 - \frac{a}{W}\right)^{-\frac{3}{2}} \tag{5}$$

It was stated that error in Eq. (5) was less than 1% [37]. As for the notched specimen, the strain intensity factor range was calculated by:

$$\Delta K_\varepsilon = f_L \Delta\varepsilon_{(x=0)} \sqrt{\pi a} \tag{6}$$

where $\Delta\varepsilon_{(x=0)}$ is the strain range at $x = 0$, where corresponds to the root of the round notch. The constant f_L was obtained by:

$$f_L = \frac{K}{\sigma_{(x=0)}\sqrt{\pi a}} \tag{7}$$