Applicability of a FIB-notch as a Small Initial Crack for Fatigue Limit Evaluation

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Abstract

In this study, we propose a method for assessing the applicability of an artificial defect as a small initial crack for fatigue limit evaluation. The proposed method is applied to drill holes and sharp notches introduced using a focused ion beam (FIB) technique in annealed 0.45% carbon steel. It is found that under rotating bending fatigue, an FIB notch can be used as a small initial crack for fatigue limit evaluation, whereas a drill hole cannot, for of ~50 μm. Here, is the square root of the area obtained by projecting the defect onto a plane perpendicular to the load axial direction. The results indicate that an FIB notch can be used as a small initial crack for fatigue limit evaluation in a greater number of materials than those in which a drill hole can be used.

1. Introduction

The fatigue limits of metals are determined by the threshold stress against the initiation or propagation of fatigue cracks. Metal components usually have various sources of stress concentration because of their configurations (e.g., holes, notches, or surface roughness) and their constituent materials (e.g., inclusions). Therefore, fatigue limits of metal components are controlled by the non-propagating behaviors or the initiation behaviors of the fatigue cracks from such stress concentrators and vary with the shape of the stress concentrators. Therefore, to design reliable metal components, it is important to know the lowest fatigue limit of variously shaped concentrators. An ideally sharp crack could be used as the highest stress concentrator. In other words, the fatigue limit value and phenomenon of the material with an ideally sharp crack should be analyzed.

Fatigue cracks are categorized by the plastic zone size in relation to the crack size [1,2]. If the former is much smaller than the latter, the fatigue crack is called a long crack. In contrast, if the former is not much smaller than the latter, the fatigue crack is called a short or small crack, where ‘‘short’’ and “small” are used with reference to two-dimensional (2D) and three-dimensional (3D) cases, respectively [1,2]. It is well known that the behavior of a short or a small crack differs that of a long crack. For example, the threshold stress intensity factor range, ΔK_{th}, for a long crack remains constant irrespective of the initial crack size, whereas that for a short or a small crack depends on the initial crack size [1,2]. The other differences between a short crack and a small crack are as follows: (i) Although the stress field near a short crack is under a plane strain condition, that near a small crack is under a plane strain condition inside the material and under a plane stress condition on the material surface. (ii) The effects of the environment on the crack tip are different. For example, the tip of a short crack such as a circumferential crack is mainly affected by hydrogen gas through a crack wake, whereas that of a small crack such as a surface crack is affected by hydrogen gas through a crack wake and from the material surface. (iii) Even if a short crack has the same stress intensity factor, K, value as a small crack, the material volume in the vicinity of a short crack tip is larger than in the case of a small crack tip; therefore, a small crack is more greatly affected by the microstructure than is a short crack. (iv) A short crack propagates in two dimensions, whereas a small crack propagates in three dimensions; therefore, the non-propagating behavior of the former differs from that of the latter. Considering points (i)–(iv), even if a short crack has the same K value as a small crack, the fatigue limit of a material with a short crack is not always the same as that of a material with a small crack. Therefore, when using a certain material in various components, the fatigue crack behaviors of long, short, and small cracks should be analyzed individually. In this regards, the fact that small defects often induce the fatigue fractures of metal components is an important one that should be kept in mind.

In previous studies, the three types – long, short, and small – of initial cracks were introduced into specimens as follows. First, long cracks were introduced by using fatigue cracks based on American Society for Testing and Materials (ASTM) standards [3]. Second, short cracks were introduced by using sharp notches with a notch root radius, ρ, less than that of the branch point, ρ_0 [4]. Third, small cracks were introduced by using annealed fatigue cracks (a fatigue crack was propagated under cyclic loads until it reached the intended size, and subsequently, stress relief annealing was applied to the specimen) [5-7]. However, this method can only be applied to materials that exhibit no microstructural change during annealing. Many other studies have simply used small holes made with a drill [8,9] or a micro electro discharge machine [10]. However, the stress concentration of a hole is too low. This implies that the fatigue limit of a material with a hole may be higher than that of one with a small crack. Therefore, small cracks have only been introduced in a few materials under limited conditions.

Recently, sharp notches introduced using a focused ion beam (FIB) technique have been used as artificial defects. The growth behavior of a fatigue crack initiated from an FIB notch was found to be similar to that of a naturally initiated crack under a low-cycle fatigue life regime [11]. However, it is difficult to investigate whether an artificial defect (such as a drill hole or an FIB notch) can be used as a small initial crack for fatigue limit evaluation. In this study, we propose a method for assessing the applicability of an artificial defect as a small initial crack for fatigue limit evaluation. Annealed fatigue cracks are used as ideally sharp cracks. The proposed method is then applied to FIB notches and drill holes in annealed 0.45% carbon steel.

2. Assessment of an Artificial Defect as a Small Initial Crack for Fatigue Limit Evaluation

2.1 Problems involved

The fatigue limit of a material with a small defect is controlled by the non-propagating behavior or the initiation behavior of the fatigue crack from a defect. Therefore, the fatigue limit values of specimens with a small defect scatter due to the difference in the material microstructure surrounding a defect in each specimen. Thus, even if the fatigue limit of a specimen with a defect is almost equal to that of an annealed fatigue crack, this may not always be the case. In other words, to investigate the applicability of a defect as a small initial crack for fatigue limit evaluation, the scatter of fatigue limits of specimens with a defect must be compared to those of an annealed fatigue crack.

Here, the fatigue failure probability is the probability relationship between a stress amplitude and a fatigue failure. Unfortunately, it is impossible to know the true fatigue failure probability, because the number of used specimens is usually limited. Therefore, it is impossible to achieve the present aim by using the raw data obtained by experiments.

2.2 Proposed method

In this study, we propose a method for assessing the applicability of an artificial defect as a small initial crack for fatigue limit evaluation in order to solve the two problems mentioned above. We focus on the state of a non-propagating crack initiated from an artificial defect. We consider the following two points: (i) the length of a fatigue crack initiated from a defect when its growth behavior can be considered to be as that of an annealed fatigue crack, a_{ic}, and (ii) the length of a non-propagating crack, a_{np}.

First, a_{ic} is described. When a fatigue crack propagates over the stress field induced by the defect, the stress intensity factor range, ΔK, of a fatigue crack initiated from a defect is the same as that of an annealed fatigue crack. Here, K is obtained by stress analysis such as the finite element method (FEM). However, the difference in the initiation and early-stage propagation between a defect and an annealed fatigue crack may produce the difference in the rest fatigue crack growth between a defect and an annealed fatigue crack. In other words, even if ΔK of a fatigue crack initiated from a defect becomes the same as that of an annealed fatigue crack, it cannot be understood whether the effective stress intensity factor range, ΔKeff, of a fatigue crack initiated from a defect can become the same as that of an annealed fatigue crack. Therefore, a_{ic} cannot always be determined by stress analysis. The fatigue crack growth behaviors are controlled by ΔKeff. Therefore, a_{ic} can be determined by comparing the fatigue crack growth behavior between a specimen with a defect and that with an annealed fatigue crack. The fatigue crack growth behaviors are analyzed by using a comparison method proposed by Kage and Nisitani [8]. Second, a_{np} is described. a_{np} can be determined by observing the non-propagating cracks initiated from a defect.

The satisfactory condition for the applicability of an artificial defect as a small initial crack for fatigue limit evaluation is $a_{ic} < a_{np}$. The scatter of a_{np} due to the material microstructure surrounding the defect is measured by considering a specimen with several defects [9]. The proposed method for assessing the applicability of an artificial defect as a small initial crack for fatigue limit evaluation affords certain advantages.

a. The satisfactory condition for the applicability of an artificial defect as a small initial crack for fatigue limit evaluation can be discussed quantitatively.
b. The investigation of the applicability of an artificial defect as a small initial crack for fatigue limit evaluation required only a few experiments.

3. Materials and Method

Annealed 0.45% carbon steel was used in order to introduce an annealed fatigue crack as an ideally sharp crack into the specimen, because its microstructure can be unaffected by annealing. Tables 1 and 2 list its chemical composition and mechanical properties, respectively. Fig. 1 shows the shape and dimensions of a specimen. Two different types of artificial defects and an annealed fatigue crack were introduced on the surface of each specimen: a drill hole (specimen A), an FIB notch (specimen B), and an annealed fatigue crack (specimen C), whose surface lengths perpendicular to the axial direction were ~100 μm. The annealed fatigue crack specimens were first notched using the FIB, following which a fatigue crack was grown under cyclic loads until its surface length reached ~100 μm. Subsequently, stress relief annealing was applied to the specimens for 1 h at 600 °C in vacuum.

The fatigue test was conducted by using an Ono-type rotating bending machine (3000 rpm) in air at room temperature. The surface crack length, including the defect length, was measured perpendicular to the axial direction by a replica method.

Table 1. Chemical composition [wt.%]

C	Si	Mn	P	S	Al	Fe
0.46	0.20	0.73	0.029	0.017	0.018	bal.

Table 2. Mechanical properties

σ_y	σ_B	Hv
360 [MPa]	633 [MPa]	185

σ_y: yield strength, σ_B: tensile strength

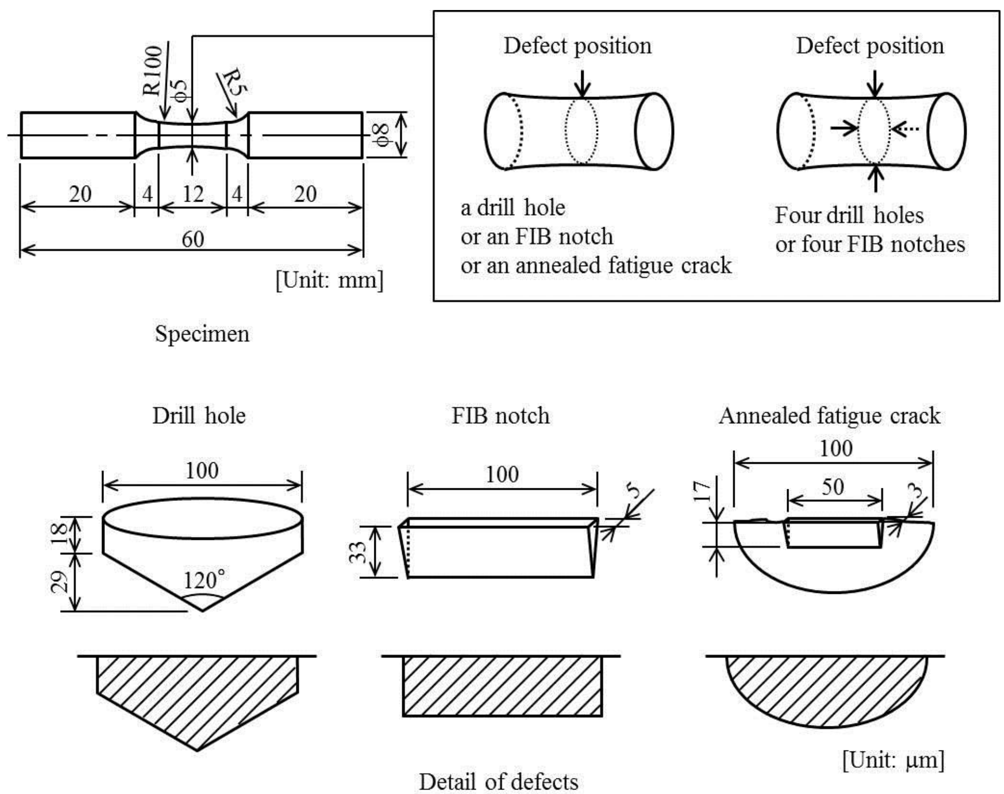


Fig.1. Shape and dimension of specimen.

4. Results and Discussion

4.1 *S-N* diagram and modified *S-N* diagram

Fig. 2 shows the relationship between the stress amplitude, σ_a, and the number of cycles to failure, N_f, for specimens A, B, and C. In this figure, the fatigue limits, σ_w, of specimens A, B, and C are 258, 250, and 255 MPa, respectively. The difference in fatigue limits may result from the difference in the $\sqrt{area}$ value. Therefore, in order to evaluate fatigue limits that are unaffected by the difference in $\sqrt{area}$, the fatigue limits were normalized by the values predicted by using Eq. 1 [1].

$$\sigma_{w,predicted} = 1.43(Hv + 120)/(\sqrt{area})^{1/6}. \quad (1)$$

Here, $\sqrt{area}$ of each specimen was obtained by observing the fracture surface. Fig. 3 shows the relationship between the normalized stress amplitude, $\sigma_a/\sigma_{w,predicted}$, and the number of cycles to failure, N_f, for specimens A, B, and C. The normalized fatigue limits, $\sigma_w/\sigma_{w,predicted}$, of specimens A, B, and C are derived as 1.18, 1.10, and 1.12, respectively. The value of $\sigma_w/\sigma_{w,predicted}$ for specimen C is ~2% higher than that for specimen B and ~6% lower than that for specimen A. The result shows that an FIB notch more closely approximates a crack than does a drill hole for the present fatigue limit evaluation.

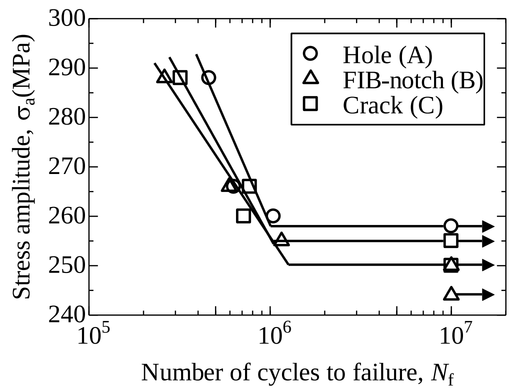


Fig.2. Relation between stress amplitude, σ_a, and number of cycles to failure, N_f, for specimens A, B, and C.

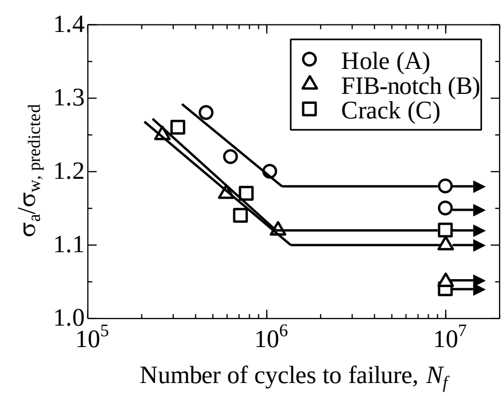
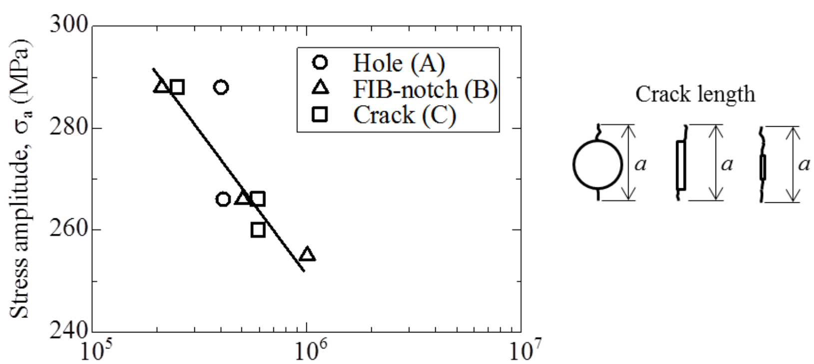


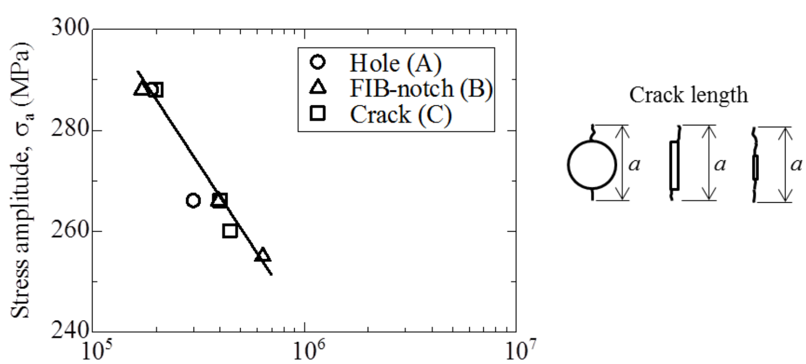
Fig.3. Relation between normalized stress amplitude, $\sigma_a/\sigma_{w,predicted}$, and number of cycles to failure, N_f, for specimens A, B, and C.

4.2 Application of proposed method

First, we determine a_{ic} by using a comparison method proposed by Kage and Nisitani [8]. Fig. 4 shows the relationship between the stress amplitude, σ_a, and the number of cycles from a certain crack length to failure for specimens A, B, and C: (a) N_f-$N_{a=130\mu m}$, (b) N_f-$N_{a=200\mu m}$. Here, a is the crack length. In Fig. 4(a), the curve for specimen B is in agreement with that for specimen C. In Fig. 4(b), the curves for all specimen types coincide. This implies that the growth behavior of a fatigue crack initiated from an FIB notch was almost the same as that of an annealed fatigue crack after the surface crack length reached 130 μm (i.e., $a_{ic,\ FIB\ notch}$ = 130 μm). Furthermore, the growth behavior of a fatigue crack initiated from a drill hole was almost the same as that of an annealed fatigue crack after the surface crack length reached 200 μm (i.e., $a_{ic,drill\ hole}$ = 200 μm.). These results show that $a_{ic,FIB\ notch}$ is shorter than $a_{ic,drill\ hole}$. Kage and Nisitani [8] also reported that the growth behavior of a fatigue crack initiated from a drill-hole (diameter: 300 μm, depth: 200 μm) was almost the same as that of a naturally initiated crack after the surface crack length reached 600 μm in the case of annealed low-carbon steel. Our results are in good agreement with their results, in that the effect of the drill hole shape on fatigue crack growth is almost negligible when the surface crack length becomes approximately twice the diameter.



(a) Number of cycles from crack length 130 μm to failure, N_f-$N_{a\,=\,130\,\mu m}$



(b) Number of cycles from crack length 200 μm to failure, N_f-$N_{a\,=\,200\,\mu m}$

Fig.4. Relation between stress amplitude, σ_a, and number of cycles from a certain crack length to failure for specimens A, B, and C; (a) N_f - $N_{a\,=\,130\,\mu m}$, (b) N_f - $N_{a\,=\,200\,\mu m}$.

Second, a_{np} and its scatter due to the material microstructure surrounding the defect are measured by considering a specimen with several drill holes or FIB notches [9]. In this study, a specimen with four drill holes and one with four FIB notches is employed. The former and latter specimen (respective fatigue limits: 258 and 250 MPa) were subjected to a reversal of constant nominal stress with an amplitude of 250 and 235 MPa, respectively. Fig. 5 shows the relationship between the surface length of the non-propagating crack and the stress amplitude for specimens A, B, and C. The surface length of the non-propagating crack, a_{np}, is defined as shown in the inset of Fig. 5. Therefore, when the non-propagating crack was not observed, the original dimension of the surface defect (i.e., 100 μm) was regarded as a_{np}. The non-propagating cracks initiated from FIB notches were observed in 7 out of 7 FIB-notches, and the surface crack lengths were greater than $a_{ic,\text{FIB notch}}$ (i.e., 130 μm). In contrast, a non-propagating crack with a surface length of 155 μm (less than $a_{ic,\text{drill hole}}$, 200 μm) was observed to be initiated from only 1 out of 6 drill holes. The results show that $a_{np,\text{FIB notch}}$ tends to be longer than $a_{np,\text{drill hole}}$.

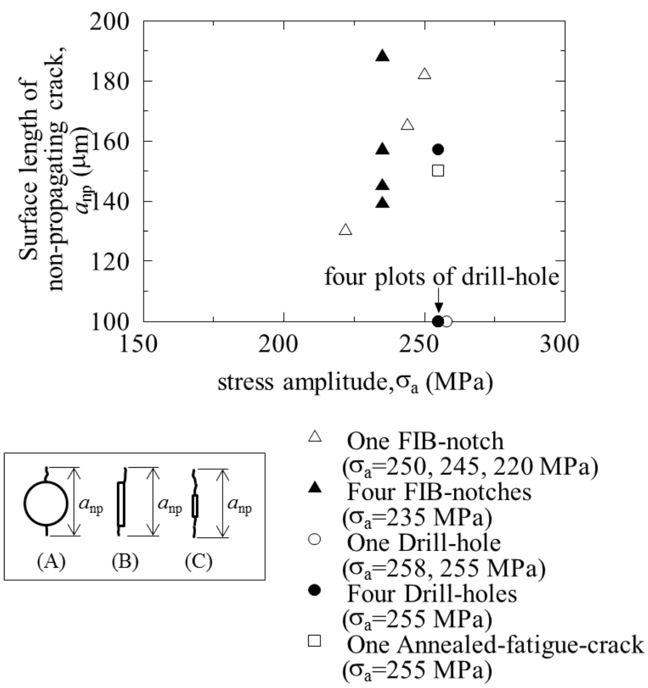


Fig.5. Relation between surface length of non-propagating crack, a_{np}, and stress amplitude, σ_a, for specimens A, B, and C.

By comparing a_{ic} with a_{np}, the fatigue crack initiated from an FIB notch is found to become non-propagating after its growth behavior closely matches that of an annealed fatigue crack. In contrast, this does not occur in the case of a drill hole under the present experimental conditions. In the case of annealed 0.45% carbon steel under rotating bending fatigue, an FIB notch can be used as a small initial crack for fatigue limit evaluation whereas a drill hole cannot for $\sqrt{area}$ of 44–65 μm. The results indicate that an FIB notch can be used as a small initial crack for fatigue limit evaluation in a greater number of materials than those in which a drill hole can be used.

The difference in the value of $\sigma_w/\sigma_{w,\text{predicted}}$ between specimens B and C appears to be due to the material microstructure surrounding the defect. In contrast, the difference in the case of specimens A and C appears to be due to not only the material microstructure surrounding the defect but also the difference in shape between a drill-hole and an annealed fatigue crack.

5. Conclusions

In this study, we propose a method for assessing the applicability of an artificial defect as a small initial crack for fatigue limit evaluation. The proposed method is applied to drill holes and FIB notches in annealed 0.45% carbon steel. It is found that under rotating bending fatigue, an FIB notch can be used as a small initial crack for fatigue limit evaluation, whereas a drill hole cannot, for $\sqrt{area}$ of ~50 μm. Here, $\sqrt{area}$ is the square root of the area obtained by projecting the defect onto a plane perpendicular to the load axial direction. The results indicate that an FIB notch can be used as a small initial crack for fatigue limit evaluation in a greater number of materials than those in which a drill hole can be used.

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