An evaluation of fatigue limit of notched specimen of a C/C composite

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Abstract. The fatigue strengths in notched specimens of carbon fiber reinforced carbon composites (C/C composites) were investigated. The fatigue limit was measured by S-N curves and load increase tests. The value of fatigue limit obtained by those methods was almost the same. Slits of several sizes were cut on both sides of a test section, and different sizes of slit length were chosen. Also, specimens with blunt-notches were used to compare the fatigue strength. The weakest fatigue limit was obtained in the case of specimens with blunt-notches. However, the stress concentration factor of those is smaller than that of slit specimens. The relationships between fatigue strengths and specimen shapes were analyzed by stress distribution. The effect of slit configuration on fatigue strength was then discussed regarding the experimental consequences. Consequently, it was discussed that the fatigue strength of the present specimens was determined depending on the damage conditions in the vicinity of the notch and on the crack initiation behavior. It is expected that the tendency of the S-N curve and fatigue limit was related to the shear damage and shear mode of the crack growth.

1. Introduction

Composites made by carbon fibers are widely used as engineering materials, and there are many kinds of carbon composites [1]. For example, there are carbon fiber reinforced aluminium composites, carbon fiber reinforced epoxy composites, carbon fiber reinforced thermoplastic composites, and so on. The carbon fiber including resin was sintered for carbonizing the resin. That was called the carbon fiber reinforced carbon compound composites or C/C composites [1-6].

The fatigue limit of slit specimens of C/C composites was investigated in the previous study by an experimental method [5]. Also, the effects of notch root radius on fatigue behavior of some notched specimens was investigated [6]. In this paper, we review the results of those studies and some discussion about the qualitative tendency of a fatigue limit of a C/C composite of machine-able type was performed. The fatigue limits of the notched specimens were discussed in this study from the viewpoints of a local shear deformation of carbon fiber, fracture constraint of composites, stress concentration, etc. In the case of metals, fatigue limit was evaluated by the S-N curve. However, in the same cases of carbon composite, the fatigue limit can be approximated by the load increase test in which single specimen was used for testing. The present study examined how the damage of the matrix and crack growth mode is related to the fatigue limit and its evaluation method.

2. Material and experimental procedure
The materials used are C/C composites of machine-able type (Grade CX-31 in Toyo Tanso Co. Ltd.). Bulk density and ash content (mass %) of that are 1.61 g/m$^3$ and 0.02%, respectively. Flexural strength (perpendicular to laminate), compressive strength (perpendicular to laminate) and tensile strength (parallel to laminate) are 90 MPa, 249 MPa and 98 MPa, respectively.

The phenol resin flew into the sheet stitched by carbon fiber. Several of those sheets were piled up and compressed under high temperature at 2000°C to make the plate for the specimen. The nominal thickness of a plate consisting of 26 sheets is 6.2 mm and the ultimate tensile strength is 98 MPa. Figure 1 shows the macroscopic appearance of the plate. The thickness $b$ and length $h$ of specimen cut from the plate were 4.2 mm and 130 mm, respectively. The width $2W$ of the specimen was changed depending on the length of blunt-notch or slit. The shapes of the test section of the specimen are shown in figure 2. Two types of specimens were made. One of them was a slit specimen with $\rho = 0.5$ mm of the root radius of the ends cut, and the other was a notched specimen with $\rho = 8$ mm of notch root radius. The loading direction was shown in figure 2 by arrow. Now, in the case of the slit specimen (figure 2(a)), slit or notch length $t$ and width $2W$ are determined to be set as the same size as the ligament $2(W-t)$. So, $2(W-t)$ was set 20 mm, the combinations of $t$ and $2W$ were 0.5 mm and 19 mm, 1.0 mm and 18 mm, 2.5 mm and 15 mm, and 5.0 mm and 10 mm.

The net stress $\sigma$ defined by equation (1) was used for the evaluation of fatigue strength.

$$\sigma = \frac{P}{2(W-t)b}$$

Figure 1. Macroscopic appearance of the carbon composite used in the study.

Figure 2. Geometry of the specimens, (a) Slit specimens ($t = 0.5, 1.0, 2.5, 5.0$ mm; $2(W-t) = 20$ mm; $\rho = 0.5$ mm ), (b) Blunt-notch specimens ($t = 7.5$ mm; $2(W-t) = 15$ mm; $\rho = 8$ mm ).

The net stress $\sigma$ defined by equation (1) was used for the evaluation of fatigue strength.

$$\sigma = \frac{P}{2(W-t)b}$$

where, $P$ is applied load and $2(W-t)b$ is area of net section.

The tendency of fatigue limit was evaluated by the two methods and whether the fatigue limit can be approximated by a simple method in the present material was discussed. One of them is the normal method of using several specimens while applying constant stress amplitude. The fatigue limit $\sigma_w$ is determined by the maximum stress where the specimen endures the $10^7$ cycles of stress repetition. Another method is called the load increase test (LIT). In this method, the approximated fatigue limit $\sigma_w'$ is obtained by using only one specimen. As shown in figure 3, the stress amplitude was increased
by 2 MPa after every application of 2x10^4 cycles. We can approximate the fatigue limit by the stress amplitude of one stage before the specimen breaks within 10^4 cycles of stress application. According to the reference [2], a notched specimen of C/C composites did not break under critical stress that is the maximum value of endurance stress of 10^4 times of stress repetition when the fatigue test was performed under constant stress amplitude. That method was applied in the present study.

The carbon fibers are stitched so that they may intersect perpendicularly in the present material. In this study, the axial direction of the specimen coincides with one of the fiber directions, so the angles between the specimen axis and fiber direction β were 0°/90°. The fatigue tests were performed with push pull by using a hydraulic testing machine with a capacity of 9.8 kN. Stress ratio (= minimum stress amplitude σmin / maximum stress amplitude σmax) was -1, and frequency was 10 Hz. The crack initiation and growth were observed by a microscope with 100 times of magnification.

3. Experimental results and discussion

3.1. Measurement results of fatigue limit σw and approximated fatigue limit σw’

Usually, the fatigue limit of a metal was determined by using plural specimens. However, in the case of carbon composites, the fatigue limit was approximated with LIT by using single specimen [2]. We measured the fatigue limit of notched specimens and the tendency of fatigue behavior was discussed.

The approximated fatigue limit σw’ was compared with the fatigue limit σw measured by S-N curve which is the relationship between the stress amplitude σ and the number of stress cycles to failure N. Then, the results were discussed from the viewpoint of the relationship between the fatigue limit and fracture behavior.

Figure 4 shows the S-N curves of the notched specimen. The results for the slit specimens and blunt notched specimen are shown. The arrow in figure 4 means that the specimen did not break by 10^7 times of stress repetition. The stress at that point was regarded as the fatigue limit σw. In the case of a slit specimen, the fatigue limit σw became lower when slit length was longer, because the stress concentration at the slit edge affected the fatigue limit. This is the same tendency as in the case of a metal [7]. In the case of ρ = t = 0.5 mm, the specimen was broken at the section without notch or slit. In the other cases, the broken area of specimen developed from notched or slit sections. Therefore, the fatigue limit in the case of ρ = t = 0.5 mm is almost the same as that of a smooth specimen because of small effect of stress concentration on fatigue behavior. Also, it is shown in figure 4 that fatigue limit
of slit specimen of \( t = 1.0 \) mm was almost the same as that of smooth specimen.

Figure 4. \( S-N \) curves of the present study.

Besides the cases where the notch length \( t \) was shorter than 1.0 mm, the fatigue limit \( \sigma_w \) was not so much different from the stress \( \sigma_4 \), that is, the endurance stress of \( 10^8 \) cycles of stress application. Therefore, it is expected that the fatigue limit of the notched specimen in the present study can roughly be approximated by the stress \( \sigma_4 \). This is related to the possibility of the approximation of \( \sigma_w \) by the approximated fatigue limit \( \sigma_w' \). The fatigue limit \( \sigma_w \) is compared with the approximated fatigue limit \( \sigma_w' \) in the cases of the blunt notched specimen and the slit specimen of \( \rho = 0.5 \) mm, \( t = 5.0 \) mm. Within the present experiment, the fatigue limits of those specimens are almost the same as shown in table 1.

Table 1. Comparison of fatigue strength measured from \( S-N \) curve and approximated method.

| Notch (mm)       | \( \sigma_w \) (MPa) | \( \sigma_w' \) (MPa) | \( \sigma_w / \sigma_w' \) |
|------------------|----------------------|-----------------------|---------------------------|
| Slit \( \rho=0.5, t=5.0 \) | 31*                  | 32                    | 0.97                      |
| Blunt notch \( \rho=8.0, t=7.5 \) | 29                  | 32                    | 0.91                      |

* Estimated value from figure 4

3.2. Relationship between fatigue limit and stress distribution

In the case of the slit specimen, the fatigue limit decreased when the slit length became longer. However, the relationship between notch radius and fatigue limit cannot be explained by the variation of maximum stress at the notch bottom.

Figure 5 shows the stress distribution calculated from the notch bottom along the axis perpendicular to the specimen axis. Two dimensional calculation was performed by the body force method [8]. We can get solution by applying boundary conditions and load to the program software of that. The symbol \( \sigma_o \) shows the applied net stress and \( \sigma_y \) the distributed stress in the loading direction. The fatigue limit of the slit specimen with \( \rho = 0.5 \) mm, \( t = 5.0 \) mm was almost the same as that of a
blunt notched specimen with $\rho = 8.0$ mm, $t = 7.5$ mm. The stress distribution of those two cases are compared in figure 5. Line 1 in figure 5 shows the distance $x$ (= 0.5 mm) where the same value of stress $\sigma_i$ is applied to cases of slit specimens with $\rho = 0.5$ mm, $t = 5.0$ mm and notched specimen with $\rho = 8.0$ mm, $t = 7.5$ mm. Within a shorter distance than that ($x = 0.5$ mm), the stress $\sigma_i$ is higher in the case of slit specimens with $\rho = 0.5$ mm, $t = 5.0$ mm. Inversely, for a longer distance than that ($x = 0.5$ mm), the stress $\sigma_i$ is higher in the case of a notched specimen with $\rho = 8.0$ mm, $t = 7.5$ mm. From those stress distributions, following situation can be expected. Even if the initial damage or cracking area in front of the notch in the case of $\rho = 0.5$ mm, $t = 5.0$ mm was created earlier, the damage expanded more slowly than in the case of $\rho = 8.0$ mm, $t = 7.5$ mm. Line 2 shows the other case where smaller initial damage was created than in the case of $\rho = 0.5$ mm, $t = 5.0$ mm. In this case, the fatigue limit becomes higher than in the case of $\rho = 0.5$ mm, $t = 5.0$ mm. Therefore, the fatigue limit is related not only to maximum stress at notch bottom but also stress distribution. Now, line 2 in figure 5 shows the distance $x$ where the same value of stress $\sigma_i$ is applied to cases of slit specimens with $\rho = 0.5$ mm, $t = 2.5$ mm and blunt notched specimens with $\rho = 8.0$ mm, $t = 7.5$ mm. From those results and the results of figure 4 ($S$-$N$ curves), it is clear that the maximum stress is not the only parameter for controlling the fatigue life.

The fatigue limit can be approximated by the load increase test. Damage to matrix and crack growth behavior can be related to that reason. So, we investigated the relationship between the damage to the matrix and crack growth behavior in the next section.

3.3. Failure mechanism of present notched specimen

Figure 6 shows the example of the growth of cracks in two cases where the fatigue life of the specimens was almost the same, that is shown in figure 4 with solid triangle symbol and open inverse triangle symbol. The shear deformation of slit specimens with $\rho = 0.5$ mm, $t = 5.0$ mm was concentrated in a narrow band which developed from the notch root. Initiation of damage was observed in the vicinity of the slit bottom, and the plural cracks were initiated in the narrow band as shown in figure 6(a). In the case of the blunt notched specimen with $\rho = 8.0$ mm and $t = 7.5$ mm, the damaged area spread in front of the notch. However a small number of main cracks grew from the notch bottom as shown in figure 6(c). Consequently, the damaged area was related to the crack expansion, and shear deformation of the matrix was limited to a narrow band in the cases of the slit specimen and blunt notched specimen.
Figure 6. Observation of cracks in the vicinity of the crack tips, (a) Slit ($\sigma_a=31.8$ MPa), (b) Schematic representation of (a), (c) Blunt notch ($\sigma_a=32$ MPa), (d) Schematic representation of (c).

Figure 7. Observation of the broken specimen (a) Slit specimen, (b) Blunt notched specimen, A thin film was stuck on the surface of test-section to ease the observation of crack.

Figure 7 shows the features of broken specimens. Figure 7(a) is the case of slit specimen with $\rho = 0.5$ mm and $t = 5.0$ mm ($\sigma_a = 31.8$ MPa, $N_f = 2 \times 10^3$) and figure 7(b) blunt notched specimen with $\rho = 8.0$ mm and $t = 7.5$ mm ($\sigma_a = 32$ MPa, $N_f = 1 \times 10^3$). The cracks in these specimens were observed within a limited area as shown in figure 6. In the final stage of fracture, the crack grew with the shear deformation along the 45 degree inclined plane in the thickness direction. Figure 8 represents the schematic representation of failure pattern in a closed part of the center axis of the specimen. The fracture process was not observed during the fatigue tests, but followings are expected from the initiation behavior of cracks (figure 6) and situation of the inclined surface of the fracture part (figure 7). During the fatigue process, the shear damage accumulated in a limited area of the matrix. Then slipping of the matrix cut fibers, and the main cracks grew by the shear mode. Finally, the specimen was broken by the shear mode in the present notched specimen.
In the case of a slit specimen, the fatigue life became longer when the slit length was shorter. Within the case of slit specimens, the stress concentration is strongly related to the stress concentration at slit bottom. However, the tendency of fatigue limit cannot be explained in the total cases of the present specimens. The fatigue limit can be related to the crack initiation patterns and crack growth mode. As shown in figures 6 and 7, the density of the crack initiation was different depending on the notch root radius. In the stage of the crack growth, the matrix deformation by shear mode in the thickness direction was expected to occurred, and the fibers were cut by the shear deformation of the matrix. That mechanism can be related to the fatigue limits of the present specimens. Thus, critical stress and deformation are expected to be related to unstable crack growth.

In the present case, the fatigue life of notched specimens or slit specimens can be approximated by the load increase test (LIT). It is expected that this reason is related to the fracture behavior of the material. The crack initiation and growth are strongly related the shear deformation of the matrix. When the crack began to grow unstably, the damage to the matrix led to the sliding direction of cracked faces in the thickness direction. It is also expected that there was a critical stress level for starting unstable shear deformation in each notch shape. The fatigue limit can be related to such behavior of cracks.

4. Conclusions
The investigation results on fatigue limit of notched specimens of the C/C composites was reviewed. Two types of specimens were used: one of them had a narrow notch which was called the slit specimen. The other one had a blunt notch with a notch radius of 8 mm. The fatigue limit can be approximated by the load increased test by using a single specimen. It is expected that this reason is related to the tendency of the fracture behavior of the material. In the case of the slit specimen, the higher fatigue limit was obtained where the notch length or slit length was shorter. However, the fatigue limit was not evaluated by only the maximum stress value at notch root, because the fatigue life of the specimen with a blunt notch was lower than that of the slit specimen in which maximum stress at notch root was low. The local shear deformation was related to the crack initiation and growth. It is expected that the fatigue limit is related to the critical level of local shear stress and shear deformation.

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