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Amplitude-Dependent Internal Friction Study of Fatigue Deterioration in Carbon Fiber Reinforced Plastic Laminates

Yoichi Nishino[a], Ryota Kawaguchi[a], Satoshi Tamaoka[a], Naoki Ide[a]*

[a]*Department of Physical Science and Engineering, Nagoya Institute of Technology, 466-8555 Nagoya, Japan*

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The amplitude-dependent internal friction in carbon fiber reinforced plastic (CFRP) laminates subjected to fatigue cycling has been measured and analyzed to convert into the plastic strain of the order of 10^{-8} as a function of effective stress. The microplastic flow indeed occurs in the stress range three orders of magnitude lower than the failure stress, and the stress-strain curves tend to shift to a lower stress as the number of cycles increases, thus indicating a decrease in the CFRP strength. The microflow stress at the plastic strain of 1×10^{-8} keeps a constant value of about 0.4 MPa in the range less than 10^3 cycles but then decreases gradually, whereas the Young's modulus evaluated from the resonant frequency is almost constant up to 10^4 cycles where only transverse cracks are found. Thus we can successfully detect the onset of fatigue deterioration by means of the amplitude-dependent internal friction.

Keywords: *CFRP, fatigue, amplitude-dependent internal friction, microplasticity, Young's modulus.*

1. Introduction

Carbon fiber reinforced plastic (CFRP) has excellent mechanical properties such as high specific stiffness and specific strength. Since weight reduction is possible by applying CFRP, it is widely used in the transportation field, especially in the aerospace field. In general, composite materials have been considered as fatigue insensitive because the conventional loading levels applied to components are far too low to initiate any local damage that could induce catastrophic failure. However, CFRP shows complicated damage behavior under tensile fatigue loading[1], and the three-stage fatigue deterioration has been observed[2]. Fatigue damage starts very early, and in this initial loading period (Stage I), there is generally a small drop in stiffness caused by transverse crack initiation. This early damage is followed by Stage II characterized by a very gradual degradation of stiffness, which results from coupling between transverse cracks and interfacial debonding/cracks, and residual strength continues to decrease throughout Stage II and into Stage III. More serious types of damage appear in Stage III, such as fiber breakage and unstable delamination growth, leading to an accelerated decline with an increasing amount of fatigue damage and finally catastrophic failure[3].

In particular, the occurrence of transverse cracks is not a direct cause of reduction in strength of the entire laminate but is a starting point of interlaminar peeling and fiber breakage which are more serious damage[1]. Therefore, in order to understand the fatigue damage behavior of the CFRP laminates, it is important to properly evaluate the transverse crack behavior. Ultrasonic testing is the most common non-destructive evaluation technique and is useful for detecting such defects as delamination in layers parallel to the surface of laminate, but is not suitable for transverse cracks and defects related to carbon fiber due to its low resolution. Thus, the establishment of non-destructive evaluation technique of damage accumulation is required to detect the onset of fatigue deterioration.

It is known that an internal friction measurement is relatively sensitive to the variation in microstructure, for example, the formation of microcracks and crack propagation. We have previously studied the amplitude dependence of internal friction and microplasticity in alumina with microcracks[4], carbon fiber reinforced SiC ceramics[5] and SiC whisker reinforced Al_2O_3 ceramics[6]. The amplitude-dependent internal friction in the composites is considered to arise from fiber pull-out or microcrack propagation. In particular, the variation in the microflow stress evaluated from the amplitude-dependent internal friction agrees well with that for the fracture stress[4]. Thus, this method is the most promising way to monitor the trend in strength change during the forerunning process of fracture in fiber reinforced ceramics or plastics. In this study, transverse crack initiation and accumulation in the CFRP laminates under fatigue loading has been evaluated focusing on the onset of fatigue deterioration.

2. Experimental

Carbon fiber reinforced epoxy prepreg sheets were prepared, and flat specimens of an angle-ply CFRP laminate were fablicated by a normal prepreg compression molding process: the lamination pattern of angle-ply was [60/-60/0]s. Specimens for fatigue tests were cut from the CFRP laminates to the size of $250\times25\times1.3$ mm^3. Fatigue tests were conducted under repeated tensile loading, using a fatigue testing system (Instron 8802), and the maximum stress level was 437 MPa

*e-mail: nishino@nitech.ac.jp

that is equal to 50% of the failure stress (stress ratio, R = 0.1). The number of fatigue cycles N was changed between 10^2 and 10^6. After the fatigue tests, the samples for internal friction measurements were cut into a rectangular shape 10 mm in width and 80 mm in length. In order to observe the fatigue defects, we employed a fluorescent penetrant inspection with the use of UV lighting, and a fluorescent dye was applied to the cross section of the samples.

Internal friction in the CFRP laminates was measured in vacuum at room temperature by means of a free-decay method of flexural vibration with both ends of the sample free and at a frequency between 350 and 420 Hz in the fundamental resonant mode. After steady-state vibration for more than 60 s, the driving signal was turned off and a free-decay curve measured using a data recorder, where the vibration is directly recorded against time. As a measure of internal friction, the logarithmic decrement was determined from the slope of a tangent to the smooth envelope of the free-decay curve as a function of the maximum strain amplitude.

3. Results

Figure 1 shows an optical micrograph of the cross section in the CFRP laminate subjected to fatigue cycling up to $N = 10^6$. In the early stage less than $N = 10^4$, in-layer transverse cracking occurs, but in the latter stage higher than $N = 10^5$, delamination cracks with a width of around 1 mm or less are also observed at the tip of transverse cracks. It can be seen that the development of transverse cracks in the inner (constrained) -60º plies proceeds at a higher rate than that for the outer (unconstrained) 60º plies.

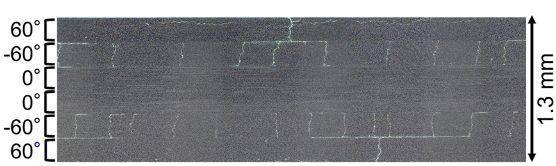

Figure 1. Optical micrograph of cross section in the CFRP laminate subjected to fatigue cycling up to $N = 10^6$, as revealed by fluorescent penetrant inspection

We define the crack density as the number of cracks in the outer plies of the CFRP laminates per unit length of the cross section. It is noted here that the internal friction measured under the flexural vibration is sensitive to the presence of defects in the outer plies of the laminates. Figure 2 shows the relation between the amplitude-independent part of internal friction and the crack density. It is remarked that the crack density for $N \leq 10^4$ is less than 0.2 mm^{-1}, and that for $N \leq 10^5$ is larger than 0.6 mm^{-1}. The internal friction is found to increase almost linearly with the crack density. Thus we believe that fatigue damage can be detected non-destructively by measuring the internal friction.

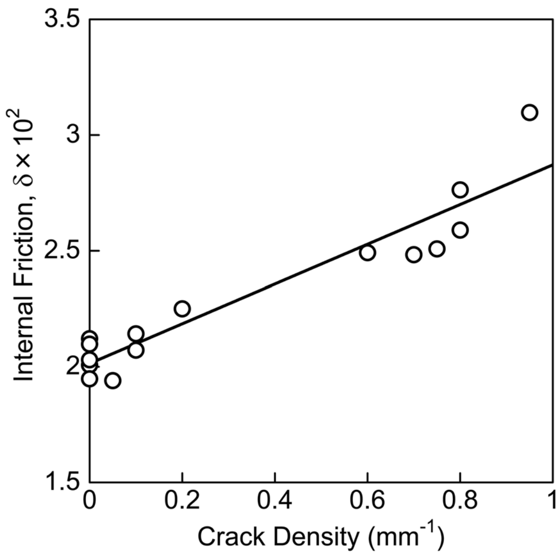

Figure 2. Relation between amplitude-independent internal friction δ and crack density in CFRP laminates subjected to fatigue cycling of $N = 10^2$-10^6

In order to evaluate the mechanical properties of the CFRP laminates subjected to fatigue cycling, we measured the amplitude dependence of internal friction. Figure 3 shows the internal friction δ plotted as a function of the maximum strain amplitude ε_{max} in the samples with the number of cycles $N = 10^2$-10^6 and the undeformed sample (N = 0). When subjected to fatigue loading up to $N = 10^3$, the amplitude-independent internal friction is almost constant and is slightly dependent on the strain amplitude. For fatigue loading of more than $N = 10^5$, the internal friction increases remarkably probably because of the occurrence of delamination cracks, and becomes strongly dependent on the strain amplitude. The amplitude-dependent internal friction is considered to arise from the relative motion between crack faces, which results in energy dissipation through the mechanical friction[4].

4. Discussion

4.1 Conversion to stress-strain responses

According to the microplasticity theory[7], we can evaluate the microplastic stress-strain responses from the amplitude-dependent internal friction. Our analytical approach[7,8] requires only an idea about the form of hysteresis loop in the stress-strain response. Direct observations by low-cycle fatigue tests and microplasticity experiments[9,10] demonstrate that the hysteresis loop under steady-state vibrations is always of a friction-type, namely a single closed loop with a symmetrical shape. The same type of hysteresis has been verified experimentally even for CFRP[11], i.e., composites incorporating plastic laminates as a matrix. The friction-type hysteresis is considered

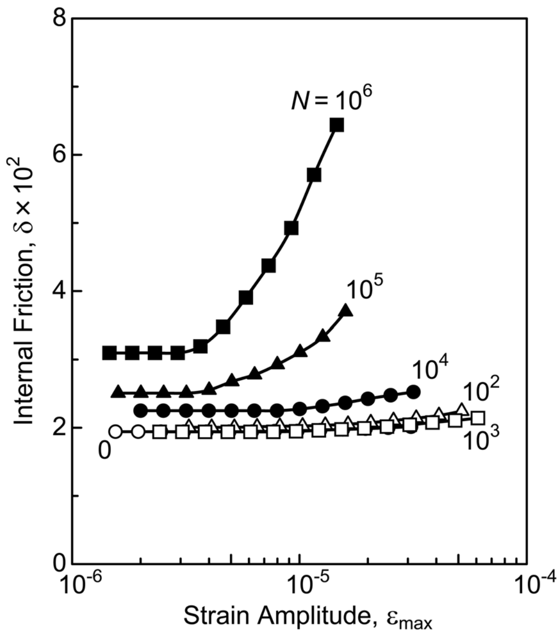

Figure 3. Internal friction δ plotted as a function of maximum strain amplitude ε_{max} in CFRP laminates subjected to fatigue cycling of $N = 10^2$-10^6 and undeformed ($N = 0$) sample

to be favored not only for various inorganic materials such as metals and alloys and ceramic materials[12] but also for viscoelastic solids like high-polymer materials.

Procedures for analyzing the amplitude-dependent internal friction are given in our preceding paper[8]. For the data analysis, the δ (ε_{max}) curves in Figure 3 are approximated by a power function of ε_{max},

$$\delta\left(\varepsilon_{\max}\right)=A\,\varepsilon_{\max}^{n}+B, \tag{1}$$

where A, B and n are fitting parameters. Then the amplitude-dependent internal friction is converted to the plastic strain ε_p as a function of effective stress σ:

$$\varepsilon_p(\sigma)=\frac{A(n+2)}{2^{n+2}n}K(n)\left(\frac{\sigma}{E}\right)^{n+1} \tag{2}$$

where E is the Young's modulus, and $K(n)$ is the correction factor for the strain distribution which is given for the flexural vibration as follows[13]:

$$K(n)=\frac{\sqrt{\pi}}{2}\frac{n+3}{3}\Gamma\left(\frac{n+4}{2}\right)\Big/\Gamma\left(\frac{n+3}{2}\right), \tag{3}$$

where Γ is the gamma function. Eq. (2) is applicable to evaluating the microplastic stress-strain responses from the internal friction data expressed by Eq. (1).

Figure 4 shows the relation between the plastic strain ε_p and the effective stress σ for the CFRP laminates subjected to fatigue cycling, corresponding to stress-strain curves in the microplastic range: the curves are obtained from the results in Figure 3. It is noted here that the value of ε_p is only of the order of 10^{-8} and as low as 0.1 % of the total strain. The microplastic flow indeed occurs in the stress range three orders of magnitude lower than the failure stress, and the plastic strain increases nonlinearly with increasing stress. There is also a general tendency for the curves to shift to a lower stress as the number of cycles increases, thus indicating a decrease in the CFRP strength due to fatigue cycling.

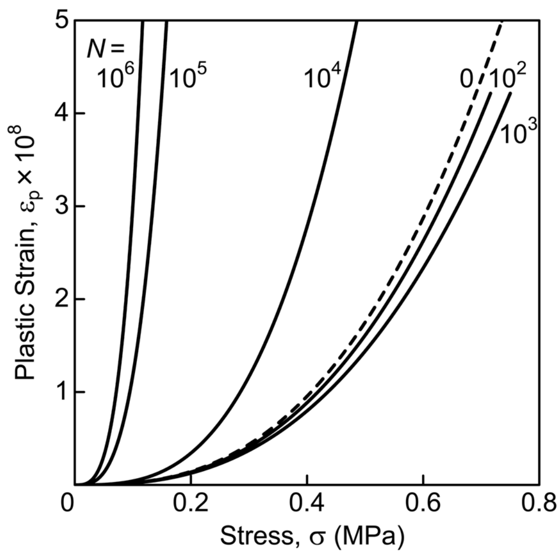

Figure 4. Microplastic strain ε_p expressed as a function of effective stress σ in CFRP laminates subjected to fatigue cycling of $N = 10^2$-10^6 and undeformed ($N = 0$) sample

4.2 Comparison between microflow stress and Young's modulus

In order to clarify the variation in the CFRP strength due to fatigue cycling, we define the microflow stress at a constant level of the plastic strain, typically $\varepsilon_p = 1\times10^{-8}$ in Figure 4. Figure 5 (a) shows the microflow stress σ plotted against the number of cycles N: for convenience, the data on the undeformed sample is plotted on the axis of $N = 10^0$. The internal friction was measured for three samples at the respective number of cycles, and the average value of the microflow stress is plotted by closed circles together with the range of variation. The microflow stress keeps almost a constant value of about 0.4 MPa in the range less than $N = 10^3$, but decreases gradually above $N = 10^4$.

For comparison, Figure 5 (b) shows the variation in the Young's modulus E evaluated from the resonant frequency during internal friction measurements: the average value is plotted by open circles together with the range of variation. The Young's modulus is constant in the range less than $N = 10^4$ and then decreases sharply. It is noted here that the number of cycles required for fracture is estimated to be approximately $N = 10^{12}$, which is much larger than the present cycling range. In reference to the three characteristic stages of fatigue damage, the border between Stage I and II where the Young's modulus drops sharply may be determined between $N = 10^4$ and 10^5, as shown by the dotted line, so that the transition to Stage II can be detected very clearly. It is seen that there is no change in the Young's modulus in Stage I, while the microflow stress exhibits a decrease even in the middle of Stage I. Therefore, the Young's modulus appears to be insensitive to transverse cracking, but decreases sharply into Stage II where delamination cracks are observed at the tip of transverse cracks, as shown in Figure 1. It is very important to properly evaluate the onset of fatigue deterioration. Remarkably, the microflow stress evaluated from the amplitude-dependent internal friction is so sensitive to damage accumulation that the fatigue deterioration can be detected even before the reduction in the Young's modulus occurs.

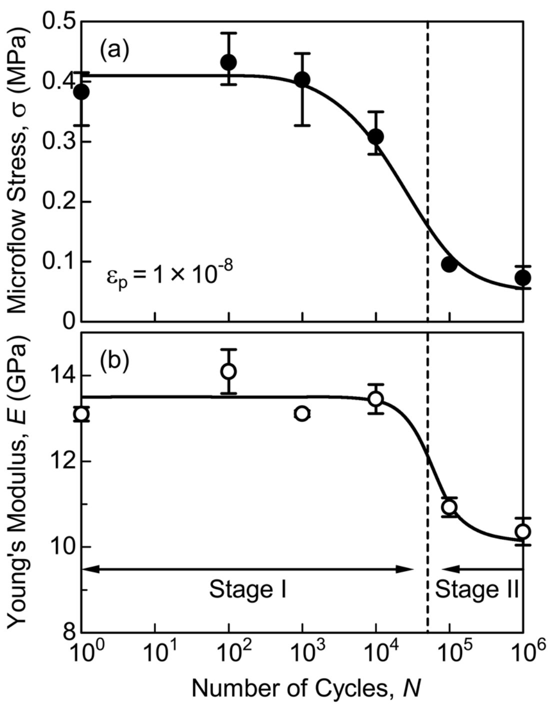

Figure 5. (a) Microflow stress σ at $\varepsilon_p = 1\times10^{-8}$ and (b) Young's modulus E against the number of cycles N. The dotted line shows the border between Stage I and II

Further, it is of interest to compare the microflow stress with the residual stress measured by tensile testing. The residual stress for FRP samples subjected to fatigue loading usually decreases towards the end of Stage II [14], but the microflow stress exhibits a decrease during Stage I. This large difference could be due to the fact that the residual stress is substantially determined by fiber breakage, whereas the microflow stress is related to microplastic deformation caused by microcracking and fiber pull-out. Therefore, the fatigue deterioration due to microplasticity can be detected much earlier than macroplasticity evaluated from the residual stress, while the stress levels are quite different from each other.

5. Conclusions

The amplitude-independent internal friction in the CFRP laminates subjected to fatigue cycling is found to increase almost linearly with the crack density, where transverse cracks are mainly observed for $N \leq 10^4$ and delamination cracks also occur for $N \leq 10^5$. Analysis of the amplitude-dependent internal friction provides the plastic strain of the order of 10^{-8} as a function of effective stress. While the Young's modulus is constant in Stage I up to $N = 10^4$ but decreases sharply into Stage II, the microflow stress keeps a constant value of about 0.4 MPa up to $N = 10^3$ and then decreases gradually even in the middle of Stage I. We conclude that the microflow stress evaluated from the amplitude-dependent internal friction is so sensitive to the accumulation of transverse cracks that the onset of fatigue deterioration can be detected before the reduction of the Young's modulus occurs. Further, the fatigue deterioration due to microplasticity can be observed much earlier than macroplasticity where the residual stress measured by tensile testing decreases towards the end of Stage II.

6. Acknowledgment

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7. References

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