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Abstract

Natural fiber reinforced composites, which can be carbon-neutral materials, have been investigated for use as alternative materials to glass-fiber reinforced plastics (GFRP). The fatigue properties of natural fiber reinforced plastics are, however, not well known. In this study, uniaxial tensile fatigue tests of unidirectional jute spun yarn reinforced polylactic acid (PLA) were conducted in order to clarify the fatigue strength. The damage and fracture morphology of composite specimens were observed to elucidate the fatigue mechanism. Results show that the fatigue strength decreases concomitantly with increasing number of cycles. The fatigue strength at 10^6 cycles was 55% of the ultimate strength, which is an almost identical percentage to that of GFRP. The fatigue failure of composite specimens was probably caused by the breakage of jute filaments at the tips of fatigue cracks in PLA. This implies that the fatigue strength of the composite was strongly affected by the fatigue properties of PLA.

Keywords

Green composite, jute spun yarn, PLA, fatigue property, fatigue mechanism

1. Introduction

Natural fiber reinforced composites, which can be carbon-neutral materials, are investigated for use as alternative materials to glass-fiber reinforced plastics (GFRP) because natural fibers have a high specific modulus and strength that is comparable with that of glass fiber. Many papers of natural fiber reinforced plastics (NFRPs) have been published using various natural fibers [1–7]. Most reports have described the use of polylactic acid (PLA) as matrix because PLA is biodegradable and made

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from renewable resources such as corn starch; therefore, natural fiber reinforced composites are often called ‘green composites’. Commercial products using green composites are available on the market. Most such products are processed with injection molding of short fibers.

Unidirectional reinforcement techniques of natural fiber spun yarn have been developed recently using pultrusion to improve the modulus and strength. These yarns are suitable for producing load-bearing beams and columns [8, 9]. The papers have reported that unidirectional reinforcement is effective in enhancing modulus and strength of green composites. Fatigue properties of unidirectional reinforced green composites should be investigated to assure the structural integrity. A few reports in the literature have described fatigue properties of natural fiber reinforced petroleum-based thermoset plastics [10, 11], but the fatigue behavior of natural fiber reinforced biodegradable resin has never been reported.

In this study, fatigue behavior of unidirectional jute yarn reinforced PLA was investigated and the fatigue mechanism was discussed. Results show that the fatigue strength decreases concomitantly with increasing number of cycles. The fatigue strength at 10^6 cycles was around 55% of the ultimate strength, which is an almost identical percentage to that of GFRP [12]. The damage and fracture morphology of composite specimens were observed to elucidate the fatigue mechanism.

2. Materials, Specimens and Testing Methods

2.1. Materials and Specimens

Water-dispersible PLA resin (PL-2000; Miyoshi Oil and Fat Co. Ltd) was used as matrix. Jute spun yarn (Asa no himo; BMS Co. Ltd) was used as reinforcement. The average diameters of filaments and spun yarn are 28 μm and 0.7 mm, respectively. Alkaline treatment of jute spun yarn with 5% NaOH was conducted for 3 h at room temperature to produce preforms [13]. The alkaline-treated fibers were washed with water, wound around a metallic plate, and dried in a furnace. Then the water-dispersible PLA resin was impregnated into the preform and the material dried for 24 h at room temperature to produce prepregs. The prepregs were laminated unidirectionally and hot-pressed at 140°C for 20 min. The number of stackings was three. Five laminates were prepared. The volume fraction was measured using an optical microscope. The volume fractions of laminates were 27, 28, 31, 43 and 44%. Scattering was not intended; it resulted from using the hand lay-up method.

The specimens for quasi-static tensile tests and fatigue tests are presented in Fig. 1. The specimen dimensions were 10.0 mm wide, 140.0 mm long and 2.7 mm thick, according to JIS K7164. The longitudinal direction corresponds to the reinforcement direction. Aluminum tabs were glued. Figure 2 shows a cross-section of the composite plate. Results showed that PLA resin was well impregnated into yarns.

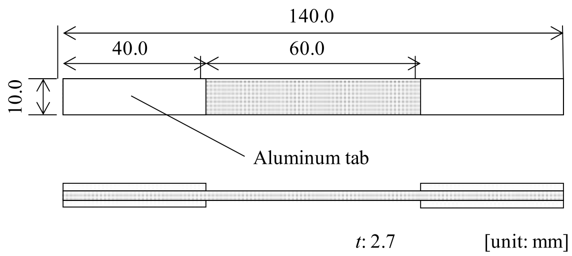

Figure 1. Specimens used for fatigue and tensile tests.

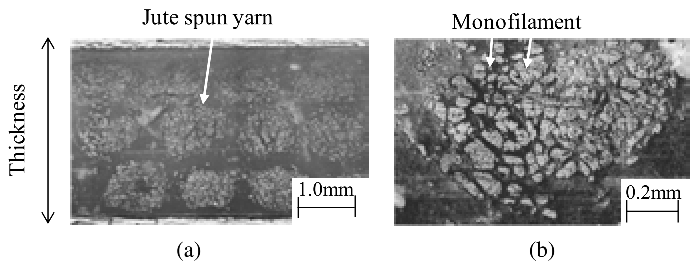

Figure 2. Resin impregnation into yarn. (a) Cross-section. (b) Resin impregnation into spun yarn.

2.2. Tensile Testing

Tensile tests were conducted to measure Young's modulus and ultimate strength according to JIS K7164. Young's modulus was measured from each stress–strain curve of $\varepsilon = 0.05$–0.25%. The cross-head speed was 1.0 mm/min. Strain gauges and an extensometer were used for measuring strain. Five specimens were prepared. The volume fraction of specimens was 44%.

2.3. Fatigue Testing

Fatigue tests with sinusoidal wave were conducted using a hydraulic servo testing machine (EM50kNT; Shimadzu Corp.). The maximum stress σ_{max} was set as 90–40% of the ultimate strength σ_B, and the stress ratio was set as 0.1. During fatigue tests, cyclic stress–strain curves were recorded at 10^3, 10^4, 10^5 and 10^6 cycles. Volume fractions of the specimens were 27, 28 and 31%.

2.4. Residual Tensile Strength

The residual tensile strength was measured after cyclic loading with $\sigma_{max} = 0.8\sigma_B$. The cyclic loading conditions were the same as those of fatigue testing. The volume fraction of specimens was 43%.

2.5. Observation Methods

The specimen surface and fracture surface were observed using an optical microscope and SEM to investigate damage propagation during fatigue testing. In addition, spun yarns in PLA resin were extracted from composite specimens to observe damage of yarns after cyclic loading. PLA resin was hydrolyzed in water at 90°C for 72 h. Ultrasonic cleaning of the extracted yarns was conducted when necessary.

3. Results and Discussion

3.1. Tensile Test

Figure 3 shows a typical stress–strain curve: it is almost linear. The average Young's modulus was 5.8 ± 0.9 GPa and the average tensile strength was 60.9 ± 3.3 MPa, where the error band is the standard deviation.

3.2. S–N Diagram

Figure 4 shows the variation in stress amplitude with number of cycles. The fatigue strength decreased concomitantly with increasing number of cycles. No fatigue limit was observed. The fatigue life increased with the increasing volume fraction of reinforcement because a higher volume fraction means lower stress in yarns and resin. The fatigue life at 10^6 cycles is around 55% of the ultimate strength; the fatigue property resembles that of GFRP [12].

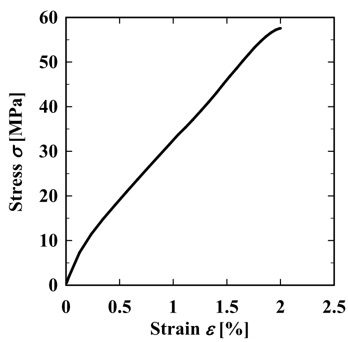

Figure 3. Typical stress–strain curve.

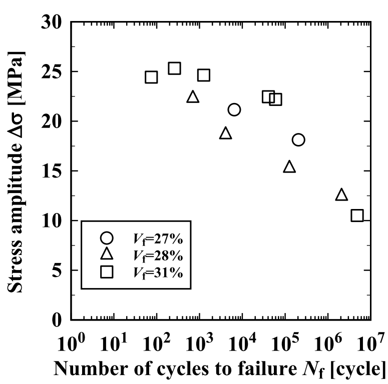

Figure 4. S–N diagram.

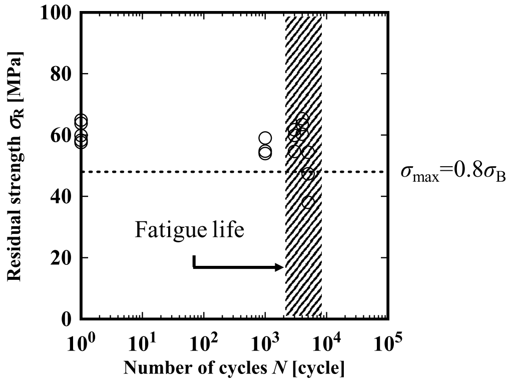

Figure 5. Residual strength after fatigue loading ($\sigma_{max} = 0.8\sigma_B$).

3.3. *Residual Tensile Strength*

The residual tensile strength after cyclic loading ($\sigma_{max} = 0.8\sigma_B$) is presented in Fig. 5. In Fig. 5, the vertical axis is residual tensile strength and the horizontal axis is the number of cycles for which fatigue tests were interrupted. For reference, the maximum stress of cyclic loading and the fatigue life with a factor of two scatter band are also shown in the figure. The residual tensile strength decreased rapidly immediately before the final failure, which implies that fiber breakage of reinforced yarn occurs immediately before the final failure.

3.4. *Damage Propagation*

3.4.1. *Macroscopic and Microscopic Fracture Observation*

Macroscopic fracture mode and fracture surface of quasi-static tensile failure and fatigue failure for high ($\sigma_{max} = 0.8\sigma_B$) and low ($\sigma_{max} = 0.5\sigma_B$) stress amplitudes are shown in Figs 6 and 7. The macroscopic and microscopic fracture morphologies were similar irrespective of loading conditions and stress amplitude, except for long delamination at low stress amplitude.

3.4.2. *Damage of Composite during Cyclic Loading*

Figure 8 shows surface cracks immediately before the fatigue failure ($\sigma_{max} = 0.8\sigma_B$). Results showed that many cracks initiated normal to the loading direction in PLA resin during cyclic loading. Breakage of jute filaments was found in front of large cracks in the PLA resin.

3.4.3. *Damage of Jute Spun Yarn during Cyclic Loading*

As the results showed, we presumed that matrix cracking preceded the breakage of jute filaments. The matrix was hydrolyzed for observation of damage in jute spun yarns. Figure 9 shows jute spun yarns extracted from the specimen presented in Fig. 8. Breakage of jute filaments was not found for yarns in a virgin specimen, nor was it found in any surface crack portion of a cyclic-loaded specimen. However, jute filament breakage was found at the front of a large fatigue crack in the PLA

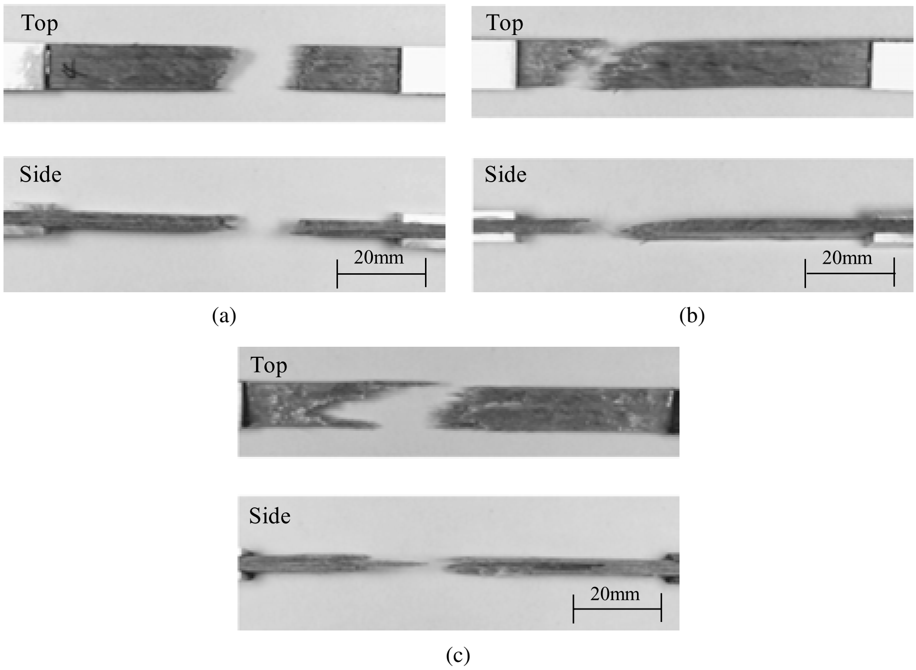

Figure 6. Macroscopic fracture morphology of the composite. (a) Quasi-static tensile test. (b) Fatigue test: $\sigma_{max} = 0.8\sigma_B$, $N_f = 6.4 \times 10^3$. (c) Fatigue test: $\sigma_{max} = 0.5\sigma_B$, $N_f = 2.1 \times 10^6$.

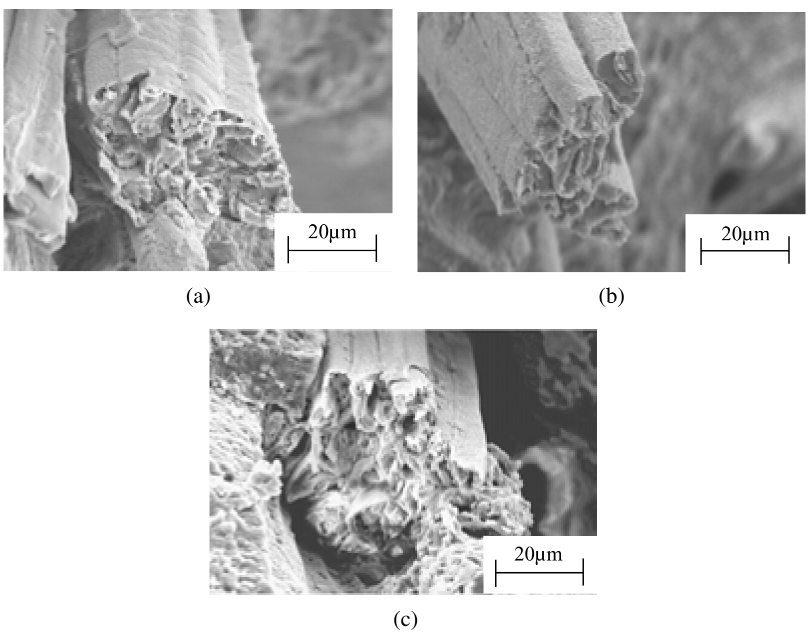

Figure 7. Microscopic fracture morphology of monofilament in the composite. (a) Quasi-static tensile test. (b) Fatigue test: $\sigma_{max} = 0.8\sigma_B$, $N_f = 6.4 \times 10^3$. (c) Fatigue test: $\sigma_{max} = 0.5\sigma_B$, $N_f = 2.1 \times 10^6$.

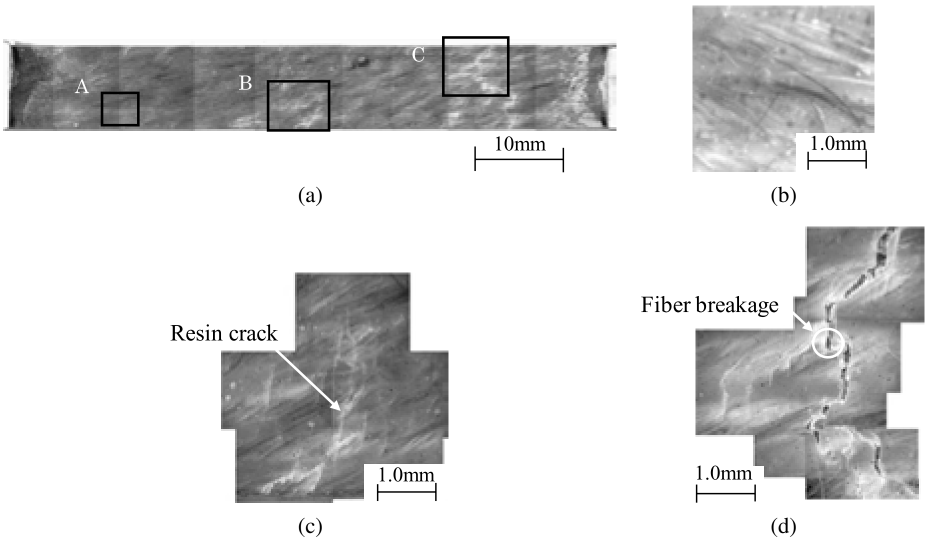

Figure 8. Specimen surface immediately before fatigue failure ($\sigma_{max} = 0.8\sigma_B$, $N = 6.2 \times 10^3$). (a) Whole specimen surface. (b) Without crack (A area). (c) With resin cracks (B area). (d) With resin cracks and fiber breakage (C area).

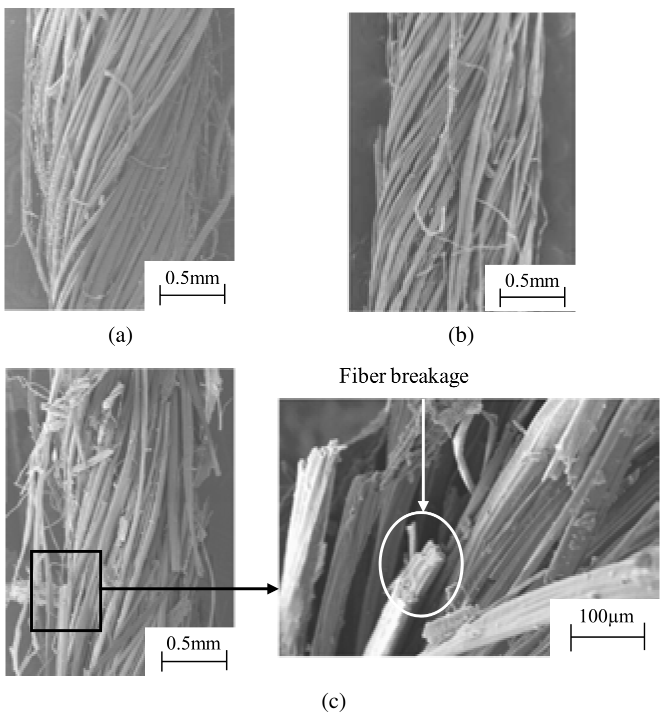

Figure 9. SEM image of spun yarn extracted from composite ($\sigma_{max} = 0.8\sigma_B$, $N = 6.2 \times 10^3$). (a) Spun yarn extracted from virgin composite. (b) Spun yarn underneath the surface without crack (A area in Fig. 8). (c) Spun yarn in front of the large crack (C area in Fig. 8).

resin. The results show that breakage of jute filaments occurred only when a matrix crack became sufficiently large to break the jute filaments.

3.5. Fatigue Mechanism

The fracture mechanism of the unidirectional jute spun yarn reinforced PLA probably proceeds as follows: fatigue cracks in PLA resin initiate and propagate from specimen surface until the cracks get to jute spun yarns; stress concentration at the crack tip engenders breakage of jute filaments; and the accumulation of fiber breakage causes the final failure. Therefore, the fatigue property of our composite would be dominated by that of PLA. Nonoyama *et al.* [14] presented S–N diagrams of PLA, although the PLA is not the same as ours. The fatigue life at any strain amplitude is equal to or less than those of our results, which supports the proposed fatigue mechanism.

The fatigue property of PLA probably dominates the fatigue life of our composite as a result of the PLA brittleness. Therefore, the usage of more ductile polymers such as PBS can be expected to enhance the fatigue life. Research work to elucidate the fatigue behavior of natural fibers is also necessary.

3.6. Cyclic Stress–Strain Curve

Typical cyclic stress–strain curves ($\sigma_{max} = 0.5\sigma_B$) are presented in Fig. 10. The cyclic stress–strain curve was almost linear irrespective of the maximum stress amplitude. The changes in the strain range and average strain with the number of cycles are presented in Fig. 11. The strain range, i.e. stiffness of composite, remained unchanged during cyclic loading. However, the average strain continued to increase. Results indicate that the creep deformation of PLA resin occurred during cyclic loading.

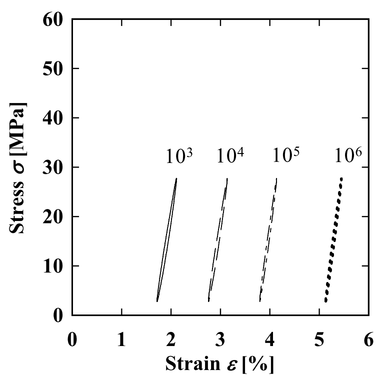

Figure 10. Cyclic stress–strain curves ($0.5\sigma_B$).

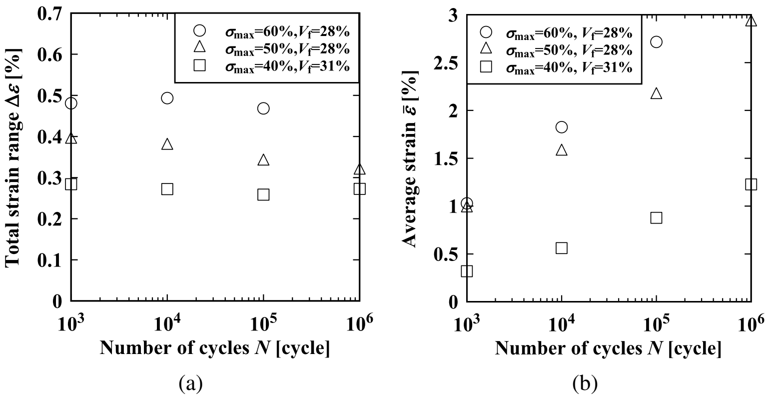

Figure 11. Changes in the total strain range and average strain. (a) Total strain range $\Delta\varepsilon$. (b) Average strain $\bar{\varepsilon}$.

4. Conclusions

The fatigue behavior of unidirectional jute spun yarn reinforced PLA was investigated, yielding the following conclusions:

(1) The fatigue strength decreased concomitantly with increasing number of cycles; that at 10^6 cycles was around 55% of ultimate strength. No fatigue limit was observed.

(2) Fatigue cracks in PLA resin seemed to cause the breakage of jute filaments. Cumulative fiber breakage can engender final failure.

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