

Effect of fiber interval on tensile strength of fiber reinforced plastics in multi-fiber fragmentation test

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Abstract

Plastics reinforced by natural fibers may be more susceptible to damage than those reinforced by carbon or glass fibers. Composite damage might be affected by fiber interval and interfacial strength between fiber and matrix resin because mechanical properties and composite damage relate to the interaction between fiber and resin. It is quite difficult to evaluate the effect of composite damage for tensile strength by using actual fiber reinforced plastic. Therefore, multi-fiber fragmentation specimens were formed by changing the number of fibers, the fiber interval, and the interfacial strength and then conducting a tensile test to evaluate the effect of fiber interval and interfacial strength on tensile strength and composite damage. Before molding the plastic, the fiber surface was modified by ethylene plasma treatment to improve adherence to the resin. The interfacial shear strength increased by 63% after 2 min. This is due to improved wettability between the fiber and polypropylene by the formation of thin film on fiber surfaces containing function groups such as $(\text{CH}_2)_n$, CH, C=C, and CO. Tensile tests on multi-fiber fragmentation specimens showed that the tensile strength decreased when the fiber intervals were widened because the tensile strength was affected by composite damage such as interfacial debonding, fiber break, crazing and whitening of polypropylene. In plasma-treated specimens, whitening as well as crazing was controlled by improving the interfacial strength between the fiber and polypropylene with an ethylene plasma treatment, which improved the tensile strength. This demonstrates that composite damage has a close relationship with fiber interval and interfacial strength, and that tensile strength might be increased by controlling them.

Keywords: multi-fiber fragmentation test, fiber interval, plasma treatment.



1 Introduction

Natural fibers have a major advantage over synthetic ones in that they are environmentally friendly, cheaper, more lightweight, and have highly specific mechanical properties [1, 2]. Natural fibers have attracted a lot of attention as reinforcement elements in polymeric resin as a result.

However, the mechanical properties of natural fibers are lower than those of high-intensity fibers such as carbon and glass, and plastics reinforced by natural fibers seem to be more susceptible to damage. Obviously, damage can negatively affect the mechanical properties of a plastic. Composite damage seems to be particularly affected by fiber interval and interfacial strength between fiber and matrix resin because mechanical properties and composite damage directly relate to the interaction between fiber and resin [3, 4]. To effectively improve the mechanical properties of plastics reinforced by natural fibers it was necessary to assess the effect of composite damage. This type of assessment is difficult to perform when using actual fiber reinforced plastics because such plastics are usually quite damaged. Therefore, multi-fiber fragmentation specimens were modeled by changing the number of fibers, fiber intervals, and interfacial strength and then conducting a tensile test.

The main focus of the present study was to clarify the effect of fiber interval and interfacial strength on tensile strength and composite damage.

2 Experimental

2.1 Materials

Ramie fiber (Chinese) was used as the reinforced fiber, and polypropylene (Nihon Matai Co., Ltd) was used as the matrix resin. The respective physicalities are shown in Tables 1 and 2. Ramie fiber has poor adhesion with matrix resin, which means the tensile properties might be unfulfilled as reinforced plastics, so a plasma treatment with ethylene gas was performed to modify the fiber surface and improve the interfacial shear strength. The treatment was carried out using ethylene gas for 2 min with a pressure of 21 Pa, power of 60 W, and frequency of 13.56 MHz. The fiber was placed in a vacuum chamber and ethylene gas was leaked in after vacuuming. A radio-frequency glow discharge was used to

Table 1: Properties of the ramie fiber.

Cellulose content [%]	85
Density [g/cm^3]	1.5
Average fiber length [mm]	80
Average fiber diameter [μm]	25
Tensile strength [MPa]	602
Young's modulus [GPa]	21

Table 2: Properties of polypropylene.

Density [g/cm^3]	0.9 - 0.91
Melting point [$^{\circ}\text{C}$]	168
Glass transition point [$^{\circ}\text{C}$]	-20



generate plasma. A polymer thin film was obtained after the addition of a polymerizing ethylene gas.

2.2 Forming of test specimen for tensile test

A molding machine with a hot-press was used to mold the test specimens into thin plate shapes for fragmentation testing. The pressure was 1 MPa, the temperature was 190°C, and the forming time was 1 minute. After molding, the specimens were fully air-cooled in an experimental laboratory. The test specimens were then cut under a constant condition with a volume content rate of fiber, as shown in Fig. 1. Fibers were arranged in a parallel manner at constant intervals, as shown in Fig. 2. The dimensions of the test specimens are shown in Table 3.

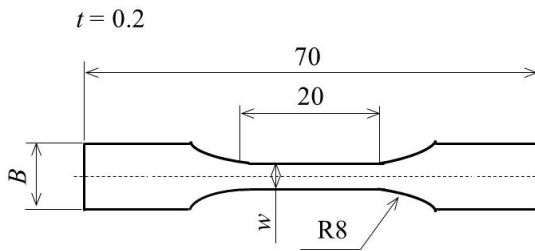


Figure 1: Schematic figure of specimen for tensile testing.

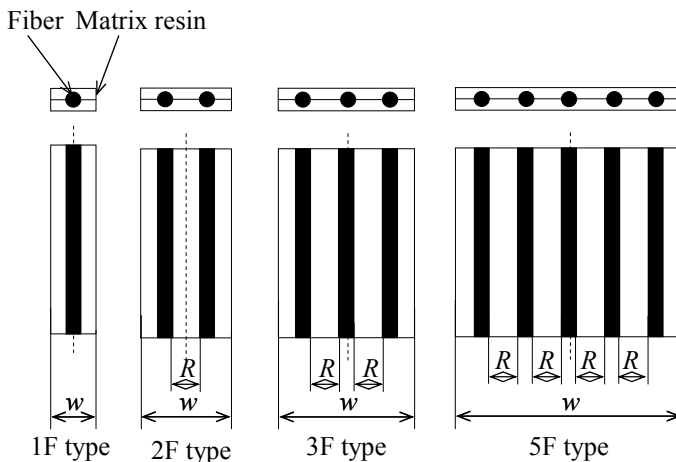


Figure 2: Schematic figure of array method of fiber in polypropylene.

Table 3: Dimensions of test specimens for tensile test.

Number of fibers	1	2	3	5
Distance of fiber interval R [mm]	0, 0.6, 1.2, 1.8			
Width w [mm]	1.8	3.6	5.4	9.0
Width B [mm]	10	12	14	18

2.3 Microbond test

Interfacial shear strength between fiber and polypropylene was measured by microbond test using a desktop-type universal testing machine (SIMADZU, Ez-test). A schematic figure of the microbond test is shown in Fig. 3. This test was performed at room temperature at a speed of 0.5 mm/min and a gauge length of 20 mm. Interfacial shear strength was evaluated using

$$\tau = \frac{F}{\pi DL} \quad (1)$$

where τ is the interfacial shear strength, F is the pullout load, D is the diameter of the fiber and L is the embedded length between ramie fiber and polypropylene. The diameter and the embedded length were measured by optical microscope before test.

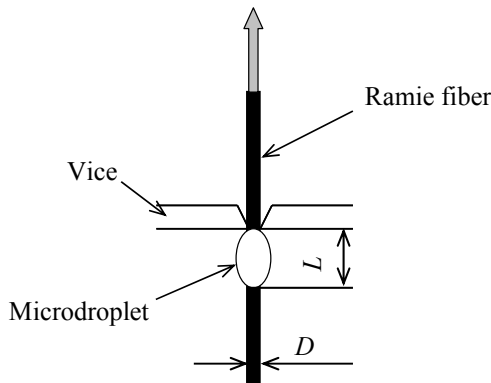


Figure 3: Schematic figure of microbond test.

2.4 Tensile test

Tensile strength was measured by static tensile test using a desktop-type universal testing machine (SIMADZU, Ez-test). The test was performed at room temperature with a tensile speed of 1.0 mm/min. Tensile strength was evaluated using

$$\sigma_c = \frac{F}{wt} \quad (2)$$

where σ_c is the tensile strength, F is the maximum force, w is the specimen width, and t is the specimen thickness. The specimen width and thickness were measured with a slide gauge and micrometer, respectively, before the test.

3 Result and discussion

3.1 Influence of ethylene plasma treatment on interfacial shear strength

The change in interfacial shear strength between fiber and polypropylene after ethylene plasma treatment is shown in Figure 4. After plasma treatment of the untreated ramie fiber, the interfacial shear strength increased in comparison to that of the untreated specimen. Particularly, it was found that the interfacial shear strength increased by 63% at 2 min in ramie fiber and polypropylene. It was confirmed to increase the interfacial shear strength between fiber and polypropylene. In a previous study, it was confirmed that thin film containing function groups such as $(CH_2)_n$, CH, C=C, and CO was formed on the ramie fiber surface by ethylene plasma treatment, and the interfacial shear strength was increased, because the wettability between ramie fiber and polypropylene was improved by formed thin film on the fiber surface. Therefore, ethylene plasma treatment was an effective method to improve interfacial shear strength between fiber and polypropylene.

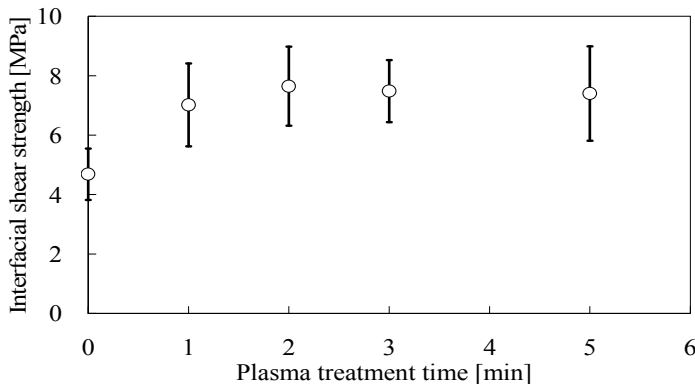


Figure 4: Change in interfacial shear strength for different ethylene plasma treatment times.

3.2 Stress-strain curve of single-fiber fragmentation specimens

The stress-strain curve resulting from the tensile test showed that the 1F-type specimens exhibited nonlinear behavior (Fig. 5). The stress-strain curve usually has nonlinear behavior in fiber-reinforced plastics when interfacial debonding occurs between a fiber and the matrix resin [5]. In the present study, SEM photographs showed clearly visible interfacial debonding. A stationary point caused by the fiber break appeared in the stress-strain curve. Therefore, the stress-strain curve was divided in an elastic deformation region, a plastic deformation of polypropylene and interfacial deformation region, and a fiber break region.

The curve's gradient ratcheted down in region B of the stress-strain curve, and the curve attained a peak in region C. This trend is discussed in terms of internal damage in natural fiber reinforced plastics.

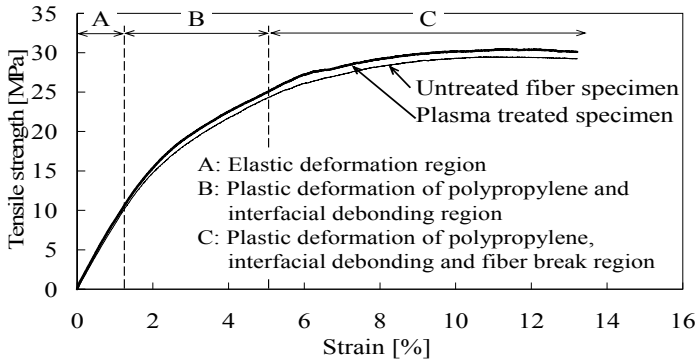


Figure 5: Stress-strain curves in 1F-type specimens.

Optical microscopic observation showed whitening and crazing around the ramie fiber embedded in polypropylene. A great deal of power was created at a certain point of the interfacial debonding region, and this power caused the early crazing. This crazing then became the origin of the composite damage, which became huge as the interfacial debonding parallel to the fiber progressed. This suggests that the ability to transmit stress between ramie fiber and polypropylene might be reduced with the expansion of interfacial debonding, and it may lead to a reduction of the gradient of stress-strain curve in region B. On the other hand, break fiber was observed in a whitening specimen, as shown Fig. 6. There have been reports that the stress field around a broken fiber can become very high during tensile testing [6]. Early crazing is caused by the tensile load, but crazing progresses due to stress concentration around the broken fiber. More severe whitening might be caused by large-scale crazing. The embedded fiber was cut to pieces by the tensile load and stress concentration, as shown in Fig. 6. The stress-strain curve finally attained a peak in region C, because the embedded fiber was cut to pieces and could not retain the tensile load.

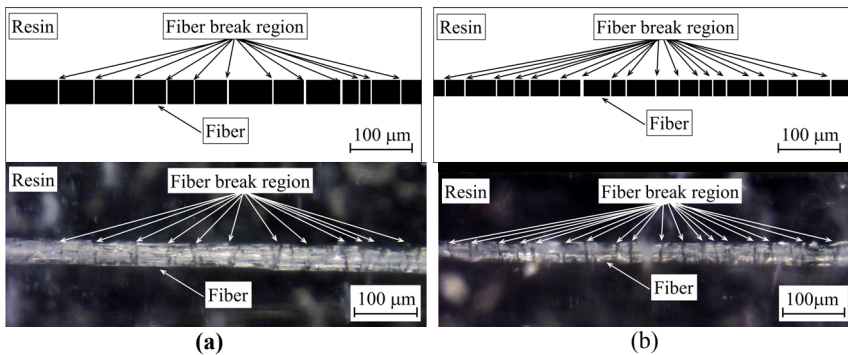


Figure 6: Optical photographs of broken fiber in the 1F-type specimen and schematic view of: (a) untreated and (b) plasma-treated specimens.

3.3 Effect of fiber interval and interfacial strength on composite damage

The stress-strain curve of the 5F-type specimen is shown in Fig. 7. This curve was also divided into an elastic deformation region, a plastic deformation of polypropylene and interfacial deformation region, and a fiber break region, the same as the curve of the 1F-type specimens. In this curve, the gradient ratcheted down when the fiber interval widened in region B. Interfacial debonding was weakened by tensile load in this region, as stated above. The ramie fiber and polypropylene were stretched jointly because they were adhesive in region A, but in region B, the effect of the polypropylene elongation was greater than in region A. This is because polypropylene is stretchier than ramie fiber. After

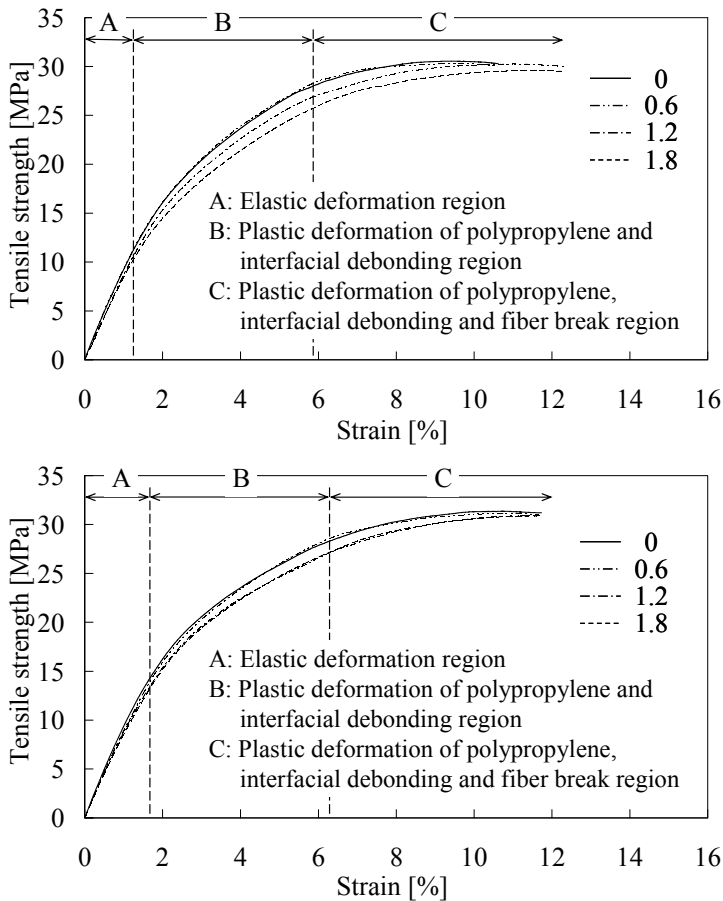


Figure 7: Stress-strain curves of 5F-type specimens: untreated specimen (above) and plasma-treated specimen (below).

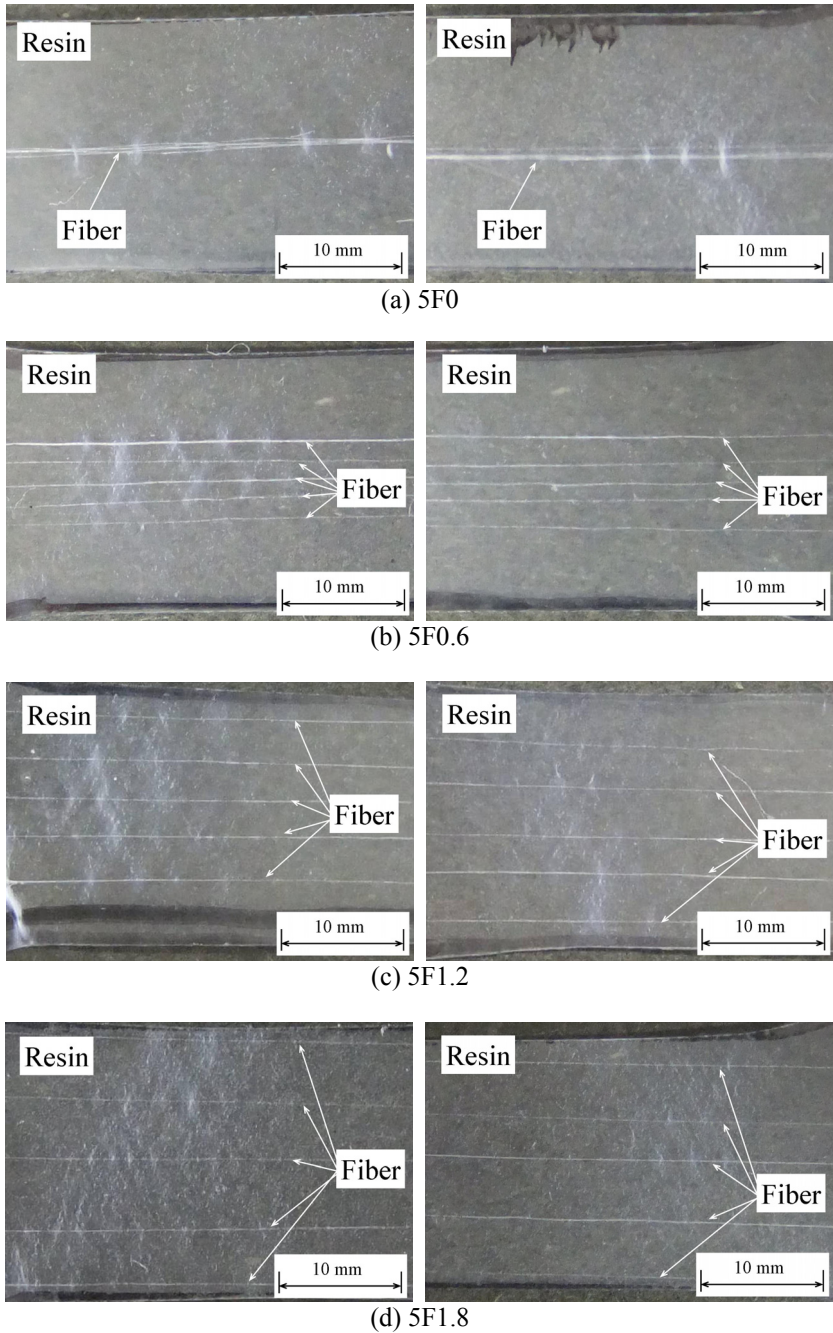


Figure 8: Photographs of 5F-type of untreated specimens (left) and plasma-treated specimens (right) after tensile test.

interfacial debonding, the gradient of the stress-strain curve became smaller due to the effect of the polypropylene elongation. This effect has a greater influence when the fiber interval widens because specimens with a wide fiber interval contain a high polypropylene content between fibers and. This is why the gradient of the stress-strain curve ratcheted down when the fiber interval widened in region B. However, this trend was improved in the stress-strain curve of the plasma-treated specimens: the interfacial strength between the ramie fiber and polypropylene was increased by ethylene plasma treatment, as previously indicated. This resulted in less interfacial debonding in region B, and the effect of the polypropylene elongation lessened in comparison to the untreated specimens. This trend became especially clear in specimens when the fiber interval widened.

Photographs of the 5F-type specimens after tensile testing are shown in Fig. 8. Whitening appeared in all specimens over a wide range when the fiber interval widened. This whitening was caused by stress concentration around the embedded ramie fiber after fiber break and depended on the polypropylene elongation after interfacial debonding. This elongation effect became stronger when the fiber interval widened because specimens with wide fiber intervals contain a high polypropylene content between fibers. In the plasma-treated specimens, the whitening is not expressly exposed, which is in sharp contrast to the untreated specimens (Fig. 8). Both the whitening and the crazing were controlled by improving the interfacial strength between ramie fibers and polypropylene with the ethylene plasma treatment.

These results agree with the results for the stress-strain curve of the 5F-type and seem to suggest that tensile strength is affected by composite damage. It also seems that tensile strength decreases with more severe composite damage.

3.4 Effect of fiber interval and interfacial strength on tensile strength

The increased rates of tensile strength due to the ethylene plasma treatment are shown in Fig. 9. The rates increased in all specimen types because the interfacial debonding in region B in the stress-strain curve (Fig. 7) was controlled by improving the interfacial strength.

In 1F-type specimens, the tensile strength increased about 2% after plasma treatment because the treatment improved the interfacial strength. A previous work by Kelly and Tyson suggested that interfacial strength could be evaluated by fiber fragmentation testing [7]. The fiber stress state in the fiber fragmentation test specimen is somewhat similar to that in an actual composite, and the fiber fragmentation phenomenon is sensitive to the level of interfacial adherence between the fiber and the matrix resin [8]. This demonstrates the consistency between microbond testing and single-fiber fragmentation test.

In the specimen of fiber interval 0, the rate of the tensile test decreased when the number of fibers increased because the interfacial surface increased when the number of fibers increased. The effect of the composite compound when the number of fibers increased in the 5F-type is shown in Fig. 9.

It was found the tensile strength increased when fiber intervals were reduced in the 2F type and, in contrast, increased when the fiber intervals were widened



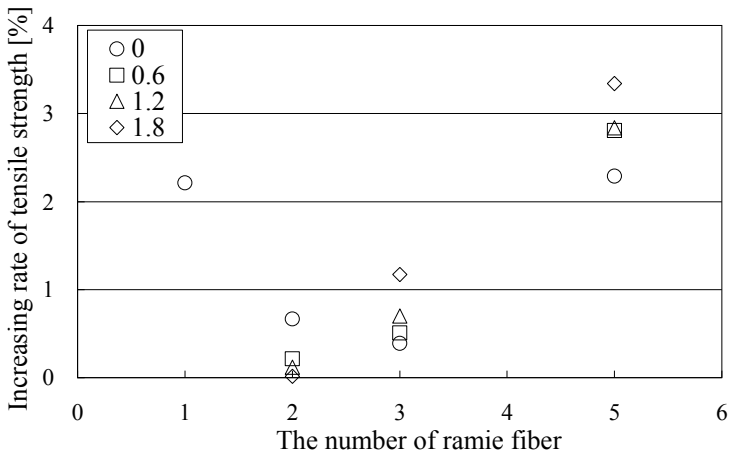


Figure 9: Increasing rate of tensile strength by plasma treatment.

in the 3F and 5F types as shown in Fig.9. The places where composite polypropylene damage in between fibers occurred increased when the number of fibers increased: one place in the 2F type, two places in the 3F type, and four places in the 5F type. Increased tensile strength was observed when composite damage places increased because the interfacial strength is already lower in untreated specimens. Improving the interfacial strength resulted in better control of composite damage, which increased tensile strength. This trend is connected to the fiber interval: the improvement effect was clearly observed when the fiber interval in 3F- and 5F-type specimens was widened.

This suggests that composite damage has a close relationship with fiber interval and interfacial strength, and that tensile strength can be increased by controlling the fiber interval and interfacial strength.

4 Conclusion

In the present study, the influence of ethylene plasma treatment on interfacial adhesion between ramie fiber and polypropylene was investigated by microbond test and single fiber fragmentation test. Moreover, it was evaluated the effect of fiber interval and interfacial strength on tensile strength by multi-fiber fragmentation testing using modified fiber and polypropylene. In microbond test, results showed that the interfacial shear strength increased by 63% in ramie fiber and polypropylene in comparison to untreated specimens. This increase was caused by the wettability between ramie fiber and polypropylene being improved by the formation of thin film on the fiber surface, thus demonstrating that ethylene plasma treatment is an effective method for improving interfacial shear strength between fiber and polypropylene.

Next, the stress-strain curve of a tensile test was divided in an elastic deformation region, a plastic deformation of polypropylene and interfacial

deformation region, and a fiber break region. Craze appeared in specimens of the plastic deformation of polypropylene and interfacial deformation region, and whitening appeared in specimens of the fiber break region. The former was caused by interfacial debonding and the latter by fiber break that reduced the tensile strength, probably because the ability to transmit stress between ramie fiber and polypropylene seems to be reduced with the expansion of interfacial debonding and the increase of fiber break.

The effect of composite damage such as crazing and whitening becomes greater when the fiber interval widens because specimens with a widening fiber interval contain a significant portion of polypropylene between fibers. This whitening appeared over a wide range when the fiber interval widened. However, in plasma-treated specimens, the whitening was not expressly exposed in comparison to untreated specimens. The generation of both crazing and whitening was controlled by improving the interfacial strength between ramie fiber and polypropylene with ethylene plasma treatment. The tensile strength subsequently improved in comparison to untreated specimens.

These results suggest that composite damage has a close relationship with fiber interval and interfacial strength and that it is possible to increase tensile strength by controlling both.

Acknowledgements

This study was supported by the High Technological Research Project on “Research and Development Center for Advanced Composite Materials” of Doshisha University and the Ministry of Education, Culture, Sports, Science and Technology, Japan.

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