Effect of hot needle punching on bending and inter-laminar characteristics of CF/PA6 composite

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Abstract

The purpose of this study is to investigate how affect the hot needle punching on bending strength and inter-laminar fracture toughness of CF/PA6. Four types of needle in which tip shape were different was used to investigate the effect of needle shape on bending strength and interlaminar fracture toughness of CF/PA6. CF/PA6 specimen was heated to soften the matrix of PA6, and then needle punching was conducted to specific number of times per unit area. The bending characteristics and interlaminar fracture toughness of CF/PA6 were evaluated by four point bending test and double cantilever beam (DCB) test, respectively. Test results showed that when punching was done using a needle with a notch at the tip, it resulted in the realignment of the yarn fibers along the out-plane direction of the punched specimen. It also led to the breakage of the fibers, owing to excessive bending. Moreover, due to the high viscosity of the matrix resin, the void was generated when the needle was pulled out from the composite. The interlaminar fracture toughness of the CF/PA6 specimens improved when punching was performed at stab density of 12 cm$^{-2}$ or more. Finally this paper revealed that the mode I fracture toughness of the needle-punched CF/PA6 specimens is dependent on both of crack bridging of the realigned fiber and pin-like resin structure.

Key words : CF/PA6, Needle punch, DCB test, Bending strength, Mode I fracture toughness

1. Introduction

Carbon-fiber-reinforced thermoplastics (CFRTPs) are known to be excellent composite materials because they exhibit high strength despite their low density, can be produced with ease (Kobayashi and Tanaka, 2010), and are highly recyclable (Zushi, et al., 2005). CFRTPs are expected to find use not only in sports gear but also in commercial vehicles (Takahashi, 2005). Generally, the fiber-reinforced plastics used for high-strength applications are made from materials with long fibers such as unidirectional or woven fabrics. In the case of long-fiber composites, owing to their anisotropic mechanical characteristics, interlaminar failure often occurs between the layers in the first or second stage of fracturing (Nishikawa, et al., 2006). Such failure is also seen in the case of CFRTPs (Obunai, et al., 2013), while CFRTPs have higher fracture toughness than Carbon-fiber-reinforced-thermosets (CFRTS). In the case of CFRTS, a number of methods for increasing the interlaminar toughness, such as the modification of the matrix (Kim, et al., 1992), stitching of reinforcements (Liu, 1991), and Z-pining (Dai, et al., 2004), have been proposed. Among these methods, the needle punching technique is known to be effective to realign the in-plane fiber to the out-plane direction (Miura and Setani, 1967). One of the authors proposed a modified needle punching technique (hereinafter referred to as hot-needle punching) in which the composites are heated and stabbed with the needle along the thickness direction (Yamamoto, et al., 2013). Compared to the conventional method, the proposed method is easily applicable to CFRTPs, because of its simplicity.

Therefore, the purpose of this study was to investigate the effects of hot-needle punching on the bending strength and interlaminar fracture toughness of a CFRTP. The CFRTP was fabricated from a prepreg, which, in turn, was made from plain carbon cloth and 0.1-mm-thick Polyamide6 (PA6) sheets. Four types of needles with tips of different shapes.
were used to investigate the effects of the needle shape on the bending strength and interlaminar fracture toughness. The CFRTP specimens were heated before being stabbed by the needles. Next, the heated specimens were impaled with a needle for a specific number of times per unit area. The four point bending test and double-cantilever beam (DCB) test were performed to investigate the bending characteristics and the mode I interlaminar fracture toughnesses of the CFRTP specimens, respectively. During the DCB test, the propagation of precracks from the sides of the specimens and the fractured surfaces were observed using an optical microscope.

2. Material and method

2.1. Materials

Plain, woven carbon cloth (TORAY, CO6343) and PA6 (TORAY, CM1017) were used as the reinforcement material and matrix, respectively. A 0.1-mm-thick PA6 sheet was fabricated from pelletized PA6 by hot pressing. The PA6 pellets were heated at 240 °C for 1 min, to avoid clefts during the sheet-forming process. Then, the softened PA6 pellets were pressed at 240 °C under 5 MPa for 3 min. First, 0.1-mm-thick PA6 sheets were fabricated by the heat-pressing method. The configuration and mechanical characteristics of the two materials are listed in Tables 1 and 2, respectively.

Table 1 Configuration of carbon cross (TORAY, CO6343).

<table>
<thead>
<tr>
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<th>TC300-3000</th>
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<tbody>
<tr>
<td>Warp yarn</td>
<td>TC300-3000</td>
</tr>
<tr>
<td>Fill yarn</td>
<td>TC300-3000</td>
</tr>
<tr>
<td>Warp ends [Count/25 mm]</td>
<td>12.5</td>
</tr>
<tr>
<td>Fill picks [Count/25 mm]</td>
<td>12.5</td>
</tr>
<tr>
<td>Areal Weight [g/cm²]</td>
<td>198</td>
</tr>
</tbody>
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Table 2 Mechanical characteristics of PA6 (TORAY, CM1017).

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<table>
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<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Density [kg/m³]</td>
<td>1130</td>
</tr>
<tr>
<td>Tensile strength [MPa]</td>
<td>85</td>
</tr>
<tr>
<td>Bending strength [MPa]</td>
<td>120</td>
</tr>
<tr>
<td>Flexural modulus [GPa]</td>
<td>3</td>
</tr>
</tbody>
</table>

2.2. Fabrication method

As mentioned previously, the CFRTP specimen investigated in this study was fabricated from a prepreg by heat pressing. In order to fabricate the prepreg itself, the carbon cloth and the 0.1-mm-thick sheet of PA6 were plied and heated for 1 min at 240 °C, in order to remelt the PA6 and impregnate the carbon cloth with it. Then, these plies were heat pressed at 240 °C under 5 MPa of pressure for 3 min. The vacuum bag molding technique was employed to fabricate the CFRTP specimen from these plies. The fiber volume fraction of the fabricated CFRTP specimen was approximately 50%. The specimen was then cut in parallel with the yarn fibers of the laminate (0°-90°) using a diamond cutter. Specimens 3.5 mm ([0°-90°]₁₁₄) and 7.0 mm thickness ([0°-90°]₂₈₈) were prepared for the bending and DCB tests, respectively.

2.3. Hot needle punching

Figure 1 shows the tips of the needles used in this study. Four types of needle with tips of different shapes were used (hereinafter referred to as "ST," "M," "V," and "R"), in order to investigate the effects of the needle shape on the bending strength and interlaminar fracture toughness. The tip notch of the needle and the yarn fibers of the test specimen were aligned. The CFRTP specimen was set in the mold and heated to 180°C before being stabbed by the needle. Once the specimen had been heated, it was punched by the needle for a designated number of times per unit area (hereinafter referred to as the stab density, \(D_S\)). The mold for hot needle punching was consisted the needle guide and spacer as shown in figure 2, and these were fixed on the heater by screw. The arrangement of needle guide hole and size of cavity at the spacer was varied to control the stab density. In the mold, the four side and top/bottom plane of specimen were constrained by the spacer and needle guide, respectively. Figure 3 shows a schematic of the relative positions of the needle and the test specimen. To eliminate the edge effect, the distance between the specimen edge and the needle stab was kept constant at 2.0 mm. The number of needle stabs made in the width direction of the specimen was also kept constant, even as the \(D_S\) value was changed. Therefore, the width of the specimen was varied to 8.0, 10.0, and 12.0 mm for \(D_S\) values of 15, 12, and 9 cm⁻², respectively. The depths of the needle stabs were controlled at 5.0 mm for the specimens for the bending and DCB tests. Hence, in the case of the bending test specimens, the needle penetrated the specimens along the
Fig. 1 Photographs and schematic illustrations of the tips of the various needles used. The "ST" needle has a cylindrical configuration; the "M" and "V" needles have a V-shaped notch at the tip; and the "R" needle has a spherical tip.

Fig. 2 Schematic illustrations of the mold for hot needle punching. The mold for hot needle punching was consisted the needle guide and spacer, and these were fixed on the heater by screw. The arrangement of needle guide hole and size of cavity at the spacer was varied to control the stab density.

thickness direction. After needle punching, the specimen was taken from the mold, and then heat pressed at 240 °C under 5 MPa of pressure for 3 min to eliminate the surface deformation due to needle stab. In this study, for ignoring the effect of heat and pressure cycle during hot needle punching on the bending and interfacial strength, the same heat and pressure cycle was applied to the virgin samples.

2.4. Bending test

The four-point bending test was performed using a universal testing machine (SHIMADZU EZ-L) in accordance with the JIS K 7074 standard. The crosshead speed, upper span length, and lower span length during the bending test were set at 5 mm-min⁻¹, 17 mm, and 51 mm, respectively. The bending strain and stress were calculated using the following equations:

\[ \sigma_B = \frac{FL}{wu^2} \]  
(1)  
\[ \epsilon_B = \frac{4.78t}{L^2} \]  
(2)

Here, \( F, \delta, L, w \) and \( t \) denote the applied bending load, deflection, span, width, and thickness of the test specimen, respectively. At least four specimens were tested to investigate the bending properties.
2.5. DCB test

The DCB test was performed using a universal testing machine (SHIMADZU EZ-L) with a specialized jig in accordance with the JIS K 7086 standard. A 25-μm-thick sheet of Kapton® was inserted at the midplane of the test specimen to simulate a crack, such that the total length from the loading point to the crack tip was 15 mm. During the test, the propagation of the simulated crack was observed from the side of the specimen using an optical microscope, and the crack extension length was measured. The mode I fracture toughness was calculated using the following equation:

\[ G_{IC} = \frac{3}{2t} \left( \frac{P_C}{w} \right)^2 \left( \frac{w\lambda_0}{\alpha_1} \right)^2 \]  

where \( P_C \), \( \lambda_0 \) and \( \alpha_1 \) denote the maximum load corresponding to unstable crack growth, the crack opening displacement (COD) compliance of the specimen, and the slope of the curve of the COD compliance and the cube of the normalized crack length, respectively. At least four specimens were tested to investigate the mode I fracture toughness.

3. Results and discussions

3.1. Bending test results

Figure 4 shows the typical bending stress-bending strain (\( \sigma_B - \epsilon_B \)) curves of the virgin (before punching) and needle-punched specimens for which the needle density, \( D_S \), was controlled to 12 cm\(^{-2}\).

The test results showed that the bending moduli and strengths of the needle-punched specimens were lower than those of the virgin sample. In particular, when the "ST" needle was used, the bending modulus and strength decreased significantly. Figure 5 shows the bending strengths of the needle-punched specimens with respect to the needle density, \( D_S \). In this figure, the average and deviation of bending strength of the virgin sample are indicated by the solid line and shaded area, respectively. In this study, the virgin samples' bending characteristics showed no significant dependence on the specimen dimensions. It can be seen that the bending strength decreased after needle punching. The diminution morphology of bending characteristics would be categorized into two parts; diminution in flexural modulus and bending strength ("ST") and diminution in bending strength ("M", "V", and "R"). Figures 6 and 7 show microscopy images of the fractured virgin and needle-punched specimens for which \( D_S \) was controlled at 12 cm\(^{-2}\). As can be seen from Figure 6, there was no significant difference between the virgin and needle-punched specimens when they were viewed from the side. In contrast, images of the fractured surfaces of the specimens revealed that the in-plane fibers of the needle-punched
Fig. 4 Typical stress-strain ($\sigma_B-\epsilon_B$) curves for the virgin and needle-punched specimens for which $D_S$ was controlled at 12 cm$^{-2}$. The bending moduli and strengths of the needle-punched specimens were lower than those of the virgin sample.

![Stress-strain curves](image_url)

Fig. 5 Bending strength with respect to stab density. The bending strength decreased after needle punching and its degree of decrease could be arranged in the following order: "R," "M," "V," and "ST."

![Bending strength vs. stab density](image_url)

specimens had undergone realignment (Figure 7). In addition, the in-plane fibers were broken in the case of the specimens punched with the "ST," "M," and "V" needles as marked with red dotted circles. In contrast, when the "R" needle was used, both the breakage of the in-plane fibers and their realignment did not occur to a significant degree. However, in all cases, voids were confirmed at each stab position as marked with white dotted circles. These results suggested that when the specimens were needle punched, the presence of an edge or a notch at the needle tip promoted the realignment of the in-plane fibers along the out-plane direction of the punched specimen. Simultaneously, the breakage of the fibers may have occurred owing to excessive bending. Moreover, when needle was pulled out from the composite, the melted resin which pushed away by stabbing flows into the area where needle is pulled out. In this stage, due to the high viscosity of the matrix resin, the voids might been generated by entrainment of the air. When the "ST" needle was used, considerable breakage of in-plane fibers was observed, so the flexural modulus decreased drastically. On the other hand, when the "M," "V," and "R" needles were used, only a few of the in-plane fibers showed breakage, so a smaller reduction in the flexural modulus was observed. It can be hypothesized that the bending strength reduced when "M," "V," and "R" needles were...
Virgin ST needle M needle

Fig. 6 Microscopy side-view images of the fractured specimens. No significant difference was observed between the various specimens.

Virgin ST needle M needle

V needle

Fig. 7 Microscopy images of the fractured surfaces of the specimens. The circles of red dots indicate areas where the breakage of the yarn and warp fibers was observed. However, when the "R" needle was used, breakage of the in-plane fibers was rare. In all cases, the voids were confirmed at the stab position as marked with white dotted circles.

used because of the voids formation.

3.2. DCB test results

Figure 8 shows the typical load-COD curves for the virgin and needle-punched specimens for which \( D_s \) was controlled at 12 cm\(^{-2}\). It can be seen that the maximum load was higher than that for the virgin sample when punching was performed with the "M," "V," and "R" needles. Figure 9 shows side-view images taken during the DCB test. It can be seen that crack bridging occurred owing to fiber realignment, when punching was performed using the "ST," "M," and "V" needles. However, when the "R" needle was used, crack bridging was not observed. Figure 10 shows the mode I
Fig. 8  Typical load-COD curves of the virgin and needle-punched specimens for which the $D_S$ value was controlled at 12 cm$^{-2}$. The maximum loads of the needle-punched samples were higher than that of the virgin sample.

Fig. 9  Side-view images taken during the DCB test; the value $D_S$ was kept at 12 cm$^{-2}$. The red dotted circles indicate areas where the bridging between the upper and lower portions of the specimen was observed.

interlaminar fracture toughnesses of the specimens after initial crack propagation with respect to the needle density. In this figure, the average and deviation of bending strength of the virgin sample are indicated by the solid line and shaded area, respectively. In this study, the virgin samples did not show a significant dependence of the fracture toughness on the specimen dimensions. It can be seen that the fracture toughness improved after needle punching at a stab density of 12 cm$^{-2}$ or higher. It can also be seen that the fracture toughness of needle-punched specimens increased with an increase in the stab density. When punching was performed using the "V" or "R" needles at a high stab density (15 cm$^{-2}$), the fracture toughness became almost twice that of the virgin sample. Figure 11 also shows the fractured surfaces of DCB specimen; $D_S$ was kept at 12 cm$^{-2}$. A flat smooth fractured surface was observed on the virgin specimen. Further, the realignment of the in-plane fiber when the "ST", "M", and "V" needles were used was confirmed. Moreover, it can be seen that the amount of realigned fiber increased in the following order: "ST" ≃ "M" < "V". This order was almost the
Mode I inter-laminar fracture toughness [kJ/m$^2$]

Stab density [/cm$^2$]

Virgin ST needle M needle

R needle V needle

Fig. 10 Mode I interlaminar fracture toughness with respect to the stab density. The fracture toughness improved after needle punching was performed at a stab density of 12 cm$^{-2}$ or more.

Fig. 11 Fractured surfaces of the DCB specimen; the stab density $D_S$ was kept at 12 cm$^{-2}$. A flat smooth fractured surface was observed on the virgin specimen. On the other hand, the realignment of the in-plane fiber was confirmed when the "ST", "M", and "V" needles were used. When the "R" needle was used, instead of fiber realignment, stress whitening of the resin was observed around the stab position.

same as that for fracture toughness. Therefore, the improvement in fracture toughness when "ST", "M", and "V" needles were used was almost explained by the crack bridging attributable to the realignment of the in-plane fiber. However, when the "R" needle was used, instead of realignment of the fiber, stress whitening of the resin was mainly observed around the stab position as indicated by red dotted circle. Generally, it is known that the stress whitening occurred when the resin was fractured with ductile manner. This result suggests that the crack closure forces was provided by stress whitening resin until its failure by mode I load. In order to investigate the reason why the stress whitening of the resin has occurred when punching was conducted with the "R" needle, the cross-section of punched area was observed. Figure 12 shows the polished cross-sections 2 mm from the edge of specimens punched with the "V" and "R" needles at $D_S = 15$ cm$^{-2}$. When the "V" needle was used, the yarn fibers were realigned, and the pin-like resin structure in the out-plane direction was confirmed. On the other hand, when the "R" needle was used, only pin-like resin structure to the out-plane direction
was confirmed. According to these results, the effects of hot-needle punching on the CFRTP can be classified into two stages: fiber realignment and resin flow. At the fiber realignment stage, the edge or tip of the needle promotes fiber re-alignment during stabbing. However, the fiber breakage occurs at the edge of needles. Therefore, when excessive fiber breakage occurs (for example, when the "ST" needle is used), the bending characteristics of CFRTP is degrade. At the resin flow stage, according to moving up of needle, the melted resin flows into the area where needle is pulled out, and this generates a pin-like resin structure to out-plane direction. When many fibers are realigned, the resin flow would be inhibited because of the presence of realignment fibers. On the other hand, the resin flow would be promoted when few fibers undergo realignment (for example, when the "R" needle is used). This pin-like resin structure also promotes crack bridging by providing crack closure forces until its failure. When the breakage of the in-plane fiber is considered, the "R" needle is effective in enhancing the mode I fracture toughness of CFRTPs.

4. Conclusions

In this study, the bending characteristics and mode I interlaminar fracture toughnesses of hot-needle-punched specimens of a CFRTP were investigated. The main conclusions of the study are the following:

(1) When punching was done using a needle with a notch or edge at the tip, it resulted in the realignment of the yarn fibers along the out-plane direction of the punched specimen. It also led to the breakage of the fibers, owing to excessive bending. Moreover, due to the high viscosity of the matrix resin, the voids were generated when the needle was pulled out from the composite.

(2) Due to fiber breakage or voids generation during hot needle punching, the bending characteristics of needle punched specimen was degraded. When using needle without a notch or edge, the diminution in bending characteristics was relatively suppressed.

(3) The fracture toughness of the CFRTP specimens improved when punching was performed at stab density of 12 cm$^{-2}$ or more.

(4) When punching was done using a needle with a notch or edge at the tip, the mode I fracture toughness was improved by the crack bridging attributable to the realignment of the in-plane fiber. When using needle without a notch or edge, the mode I fracture toughness was improved by the crack bridging attributable to the pin-like resin structure in the out-plane direction.

(5) When the breakage of the in-plane fiber is considered, the needle without a notch or edge at the tip is effective to enhance the mode I fracture toughness and suppress the degradation in bending characteristics of CFRTPs.

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References


