DEVELOPMENT OF AUTOMATIC PLACEMENT MACHINE FOR CFRTP TAPES USING MACHINE STITCHING

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Abstract

An advanced automated tape placement (A-ATP) method was developed for continuous carbon fiber reinforced thermoplastics (CFRTP) tapes by using a modified inexpensive industrial embroidery machine. This method allows us to place and fix the CFRTP tapes stably by machine stitching at the desired position with the suitable fiber direction and length. The A-ATP, using “tape type” materials, is more useful for producing near net-shape blanks for compression molding than conventional “sheet type” materials. Therefore, it can reduce the production cost due to higher material yield and lower machine cost compared to other expensive ATP machines. In order to confirm the effect of A-ATP, a three-point bending test was conducted for unidirectional (UD) laminates using CF/PA6 tapes. The flexural properties of the stitched UD laminates were almost the same as those of UD laminates fabricated using the conventional CF/PA6 sheets under the same fiber volume fraction. In addition, it is estimated that the A-ATP method can reduce material waste by 50% and processing time by 75% compared to the fabrication using the conventional CFRTP sheets in a specific automotive part.

Introduction

Automotive industry has been required to develop fuel efficient vehicles because of strict environmental regulations of CO₂ emissions, and has therefore adopted lightweight materials such as carbon fiber reinforced plastics (CFRP). In particular, carbon fiber reinforced thermoplastic (CFRTP) is expected to be a key material for automotive parts due to the high productivity and recycling properties in comparison with carbon fiber reinforced thermoset (CFRTS). Therefore, intermediate materials and high speed molding technology for CFRTP has been actively developed [1-4].

In order to use expensive CFRTP to produce cars, however, the production costs have to be reduced significantly. It is well known that a large amount of waste is generated after the material is cut in the manufacturing process using the most common wide sheet type of intermediate material, as shown in Figure 1 (a). This is regarded as a major factor of increasing material costs. Accordingly, automated tape placement (ATP) is becoming one of the effective
lamination methods for the intermediate materials. As shown in Figure 1(b), narrow tape type of material can be placed and fixed at the desired position with the suitable fiber direction and length by using automatic placement machine. Consequently, the waste left after the material is cut is substantially reduced with the lamination with “tape type” materials as compared to that with the conventional “sheet type” materials.

Several ways of the automatic placement for CFRTP tapes have been developed, in which non-adhesive CFRTP tapes are joined by hot gas, laser or ultrasonic welding [5-11]. However, when the ATP with hot gas or laser is used, the mechanical properties of the laminates may decrease in association with the low crystallinity of the matrix resin due to incomplete melting or excessive cooling rates [8, 9]. In ultrasonic welding, the bonding strength between the welded materials is relatively low because of spot bonding, therefore it is expected that the laminated materials are likely to peel off during the pre-heat or material transfer process before compression molding.

The purpose of this study is to develop an advanced ATP method optimally designed for narrow CFRTP tapes. A new tape placement machine for rapid and low-cost lamination was developed using machine stitching by modifying inexpensive industrial embroidery machine. This paper firstly describes the outline of the developed tape placement method and machine. Subsequently, unidirectional (UD) laminates were fabricated by the placement machine using narrow tape material, the flexural properties of which were evaluated in comparison with those of the laminates using conventional sheet type material. Finally, the effect of the method on the reduction for material waste and processing time during tape placement was discussed.

Advanced Automatic Placement Method for CFRTP Tapes

Tape Placement Method Using Machine Stitching

Figure 2 indicates the outline of the advanced automated tape placement (A-ATP) method developed in this study [12]. As shown in this figure, a narrow CFRTP tape is placed and fixed at the both ends of the tape by machine stitching on the base cloth or film of resin, where the tape is cut to the suitable length adjusted for the product shape so that the excess part outside the product, corresponding to material waste, is minimized. This placement process is repeated with the change of fiber orientation according to stacking sequence.

Development of A-ATP machine

In order to apply the A-ATP method to the actual product process, some dedicated automatic placement machine is required for the narrow CFRTP tapes. In this study, a high-speed automatic tape placement machine shown in Figure 3 (a) was developed. This is fabricated by modifying Tailored Fiber Placement Machine TCWM-T01 made by Tajima Industries Co., Ltd.
Figure 2: Schematic illustration of narrow CFRTP tape placement by A-ATP method.

Figure 3: Advanced automated tape placement machine using machine stitching.

(a) Appearance of A-ATP machine.

(b) Material cutter.

(c) Material feeder.
which is based on conventional embroidery sewing machine. It has a movable XY table and a 360° variable rotary table for changing fiber orientation, and also has two devices optimally designed for CFRTP tape, such as material cutter (Figure 3 (b)) and feeder (Figure 3 (c)).

By using the A-ATP machine, the following advantages can be obtained:

- Equipment installation cost for tape placement can be suppressed because the A-ATP machine was fabricated by modifying inexpensive embroidery machine.
- Non-adhesive CFRTP tape can be firmly fixed to substrate without melting process of the material.
- It is possible to place and laminate CFRTP tapes rapidly and automatically.

On the other hand, there are concerns that the mechanical properties can be reduced for the laminate fabricated with the A-ATP machine. This is because the fiber volume fraction decreased due to the use of subsidiary materials of resin such as the base cloth/film and stitching thread, and also because the carbon fiber may be broken in associated with the needle penetration. In particular, the reduction in the mechanical properties is a major impact on the function and reliability of the product, therefore the stitching have to be carried out at the excess part outside the product.

Fabrication of UD Laminates and Evaluation of Its Flexural Properties

Material

Using a unidirectional CF/P6 semipreg in which PA6 resin is partially impregnated in the bundle of carbon fiber (Mitsubishi Rayon TR50S), two types of material with different width were prepared to fabricate UD laminates. One is the “sheet type” material shown in Figure 4 (a). This is the received original material of conventional sheet with the width of 300mm. The other is “tape type” material shown in Figure 4 (b), in which the sheet type material was slit to relatively narrow width of 50mm.

![Figure 4: Appearance of CF/PA6 intermediate material.](image_url)
Experimental Procedure

As shown in Figure 5, the tape type material was placed on the base film of PA6 and fixed near the both ends by machine stitching, and finally was cut to the length of about 300mm. Subsequently as a single layer, a total of 6 tapes were arranged in parallel on the base film.

Figure 6 shows the tape stacking pattern employed in this study. The tape material was laid upward by bricklaying to stack stably, finally 8 layers of tapes were laid up on the base film. Furthermore, in order to fabricate a laminate plate with the thickness of 2mm for flexural testing, it is necessary to stack a total of 16 layers of tape. Therefore, using two stacked tapes of 8 layers, these were laminated so that both base films faced together.

![Figure 5: Schematic illustration of placing CF/PA6 tapes to fabricate unidirectional laminate.](image)

![Figure 6: Schematic illustrations of stacking pattern of CF/PA6 tapes.](image)

Figure 7 shows the molding process and condition to fabricate UD laminates. Both of the stacked tapes and the sheet materials with the same number of layers were cut out to fit the cavity dimensions of mold (length 250mm × width 250mm). After drying at 50 ℃ for 8 hours,
compression molding was carried out to these materials at 250 °C for 5 minutes with a pressure of 3 MPa, where a closed-mold was adopted to prevent flow out of the matrix resin and carbon fibers during molding. The fabricated UD laminates using the tape and sheet type material are referred to as the tape laminate and sheet laminate, respectively.

From the both laminates, flexural specimens were cut out to a rectangle of 100×15mm with the thickness of about 2mm so that the longitudinal direction was parallel to the fiber direction (0 °). A three point bending test was conducted to these specimens according to JIS K 7074, with a span of 80mm and a test speed of 5mm/min.

Results and Discussion

Table I shows the measured fiber volume fraction, \( V_f \), for the tape and sheet laminates. It can be seen that the \( V_f \) of the tape laminate is 5% smaller than that of the sheet laminate. This is probably due to the use of the subsidiary materials such as the base film and the stitching thread in the tape laminate, because these materials are made of the same resin of PA6 as the matrix of the UD laminate.

| Fiber volume fraction, \( V_f \) (%) |
|-----------------------------------|-----------------|-----------------|
| Tape type                         | 53              | 58              |
| Sheet type                        |                 |                 |

Figure 8 shows the flexural modulus and strength in the UD laminates, where the flexural modulus, \( E \), and strength, \( \sigma_U \), are normalized by the value of the sheet laminate, \( E_{\text{sheet}} \), and, \( \sigma_{U_{\text{sheet}}} \), respectively. From this, both the flexural modulus and strength in the tape laminate resulted about 5% less than the each values of the sheet laminate plate, in connection with the 5% reduction of \( V_f \) in the tape laminate as already shown in Table I.

In order to compare the flexural properties in the tape and sheet laminates under the same fiber volume fraction, the flexural modulus and strength in the sheet laminate at the same \( V_f \)
value as the tape laminate was estimated by law of mixture. The axial flexural modulus $E_f$ of the carbon fiber itself was calculated by substituting the flexural modulus $E$ (\(= E_{\text{sheet}}\)) the fiber volume fraction $V_f$ of the sheet laminate and modulus of the matrix resin ($E_m = 2.6\text{GPa}$) \[13\] for equation (1). Subsequently, from the modulus values of $E_f$ and $E_m$ and the measured fracture strain, the ultimate stresses of the constitutive materials $\sigma_{fU}$ and $\sigma_{mU}$ were obtained from equation (2) as shown in Table II. From these parameters and equation (1) and (2), the flexural modulus and strength of the sheet laminate was estimated in the any $V_f$ values.

\[ E = V_f E_f + (1 - V_f) E_m \]  \[ \sigma_{U} = V_f \sigma_{fU} + (1 - V_f) \sigma_{mU} \] (1)  (2)

Figure 8: Comparison in flexural modulus/strength between tape and sheet laminates.

<table>
<thead>
<tr>
<th>Fiber, $E_f$</th>
<th>Matrix, $E_m$</th>
<th>Fiber, $\sigma_{fU}$</th>
<th>Matrix, $\sigma_{mU}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>194</td>
<td>2.6 [13]</td>
<td>2925</td>
<td>39</td>
</tr>
</tbody>
</table>

Table II  Flexural modulus and ultimate stress of both fiber and matrix in sheet laminate.
The measured and estimated values of the normalized flexural modulus $E / E_{\text{sheet}}$ and strength $\sigma_{U} / \sigma_{U_{\text{sheet}}}$ are plotted against the fiber volume fraction in Figure 9. From this, it reveals that there is no significant difference in both the flexural modulus and strength between the experimental value of the tape laminate and the estimated value of the sheet laminate under the same $V_f$ value. This means that the decrease in the flexural modulus and strength of the tape laminate depends on the decrease in the $V_f$ due to using the subsidiary materials of the resin film and thread. However, the flexural properties in the tape and sheet laminate are substantially equal under the same $V_f$ value, therefore it is expected that the mechanical properties of the tape laminate can be improved if some technical improvement is conducted to prevent the decrease in the fiber volume fraction for the A-ATP process.

**Figure 9:** Relationship between flexural modulus/strength and fiber volume fraction.

### Evaluation of Material Waste and Processing Time

For the purpose of evaluating the productivity of the A-ATP method, a material waste and processing time during tape lamination was estimated in a specific automotive part, transverse member. As shown in Figure 10, this is one of the automotive part to improve steering stability by fixing the right and left frame behind the front wheels, it can be reduced the weight 40% under the same stiffness by substituting CFRTP for the present steel [14].

**Transverse member**: The parts fixing right & left frame behind front wheels, to improve steering stability

**Figure 10**: A trial for light-weighting using CFRTP in an automotive part (transverse member) [14].
The material waste and laminating time during the A-ATP process in the fabrication of a blank of 25 layers with the size of 1100×420mm were estimated. These are shown in Table III, in comparison with those of the manual lamination with the conventional sheet type material [14]. From this, it can be seen that the tape placement with A-ATP reduces the material waste and processing time by 50% and 75% respectively, as compared to the manual sheet lamination. It follows that A-ATP can be effective method as a low-cost, high-speed and low environmental load manufacturing process for automotive industry.

<table>
<thead>
<tr>
<th>Tape type</th>
<th>Material waste (kg)</th>
<th>Laminating time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tape type</td>
<td>1.3</td>
<td>130</td>
</tr>
<tr>
<td>Sheet type</td>
<td>2.6</td>
<td>480</td>
</tr>
</tbody>
</table>

**Summary**

As advanced automated tape placement (A-ATP) method optimally designed for narrow CFRTP tapes, a new tape placement machine for rapid and low-cost lamination was developed using machine stitching by modifying inexpensive industrial embroidery machine. The effects of the A-ATP method were evaluated in the aspect of mechanical properties of fabricated UD laminates and productivity. The main results obtained are as follows:

- As a result of three-point bending test conducted to the UD laminate using CF/PA6 tapes stitched by the A-ATP method, the flexural modulus and strength of this laminate were almost the same as those of the UD laminate fabricated using the conventional CF/PA6 sheets under the same fiber volume fraction.

- In comparison with the manual lamination process with conventional CFRTP sheets, it is estimated that the A-ATP method can reduce material waste by 50% and processing time by 75% in a specific automotive part. Therefore, the A-ATP can be expected to be an effective method as a low-cost, high-speed and low environmental load manufacturing process for automotive industry.

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**Bibliography**


