EFFECT OF VARIOUS KNITTING TYPES ON IMPACT PROPERTIES OF TEXTILE COMPOSITES

Ö. Demircan1*, T. Fujimura2, S. Ashibe2, T. Kosui2, A. Nakai3

1 Advanced Fibro-Science Division, Kyoto Institute of Technology, Kyoto, Japan
2 R&D New Technology Applications, Shima Seiki, Wakayama, Japan
3 Department of Mechanical Engineering, Faculty of Engineering, Gifu University, Gifu City, Japan

*Corresponding author (odemircan79@gmail.com)

Keywords: biaxial weft knitted composites, impact properties, thermoplastic composites

Abstract
The purpose of this study was to investigate the knitting techniques in order to increase the mechanical properties of biaxial weft knitted composites. Five different types of knitting specimens (normal plain knitting, interlock, tuck, tuck-miss and interlock2) were fabricated and finalized on the compression molding machine. After production of composite panels, three-point bending impact tests were conducted on specimens. Relationship of the total absorbed energy from three-point bending test and from three-point bending impact test was studied and relationship between energy after maximum load and volume fractions of composites was also investigated. Further, the fracture behaviours of specimens were studied and fracture aspects supported the three-point bending impact test results. Volume fraction of weft fibers of interlock2 was the highest and length of straight part of loop shape was the longest in the interlock2 compared to other four types of specimens. Because of the higher volume fraction and the longer length of the straight part of the loop shape of the interlock2, composites with biaxial weft knitting preforms consisting of knitting type of interlock2 had higher three-point bending impact properties than those other four types (plain, interlock, tuck and tuck-miss) of composite structures.

1 Introduction
Knitted fabrics are constructed by loops which can extend easily and slide which generates a higher degree of deformability in comparison with other types of reinforcements. Weft knitted fabrics offer great possibilities of near-net-shape structures, by this way manual work can be reduced [1]. Due to the cost-effective manufacture offered by knitting technology, the using of knitting with advanced fibers, such as glass and aramid, to produce near-net-shape preforms has in recent years received increasing interest [2]. Knitted composites are generally considered to have inferior mechanical properties due to their highly looped structure and low fibre volume fraction. However, the attractive properties, such as those requiring high energy absorption, or in cases where the component is complex in shape and demands exceptional formability, can be achieved by using knitted composites [3]. In order to improve the mechanical properties, such as strength and stiffness, of weft knitted fabric, straight yarns both in weft and warp directions can be integrated. These types of reinforcements are called biaxial weft knitted (hereinafter referred to as “BWK”) structures. Weft and warp yarn layers are held together by a stitching yarn system in BWK fabrics. Reinforcing yarns, e.g. glass or aramid fibers, can be used within all yarn systems [4]. Nowadays, thermoplastic composites are being used in various industries such as automotive, wind turbines etc. The most important advantages of thermoplastics are their potential for rapid, low-cost and mass production of reinforced composites. On the other hand thermoplastic composites have very high viscosity (usually 500-5000 Pa s) which makes the processing of thermoplastic matrix composites be difficult. Therefore some techniques, such as commingled yarn, were developed in order to improve process ability of thermoplastic composites. The matrix fiber will be mixed with reinforcing fiber in commingled yarn technique and this technique was proven to be a cost-effective method for processing of thermoplastic composites [5-6].
Therefore, the commingled yarn technique was chosen in order to fabricate the BWK preforms. Some research has been done to find out consolidation quality of GF/PP commingled yarn based composites [7-8].

Knitted fabric reinforced thermoplastic composites with commingled fibers were studied by some researchers [9-10]. Tensile, three-point bending and impact properties of textile-inserted PP/PP knitted composites using injection-compression molding were reported by Khondker et al. [11].

The impact properties of weft knitted fabric reinforced composites were investigated by several researchers [12-15]. In comparison with composites manufactured from a single layer of fabric, knitted composites with an increased number of fabric layers demonstrated improved impact damage resistance and fracture toughness [16-18].

The bending and impact properties of BWK thermoset composites were reported by Demircan et al. [19]. This study showed that fabric became more shock-absorbent using stronger reinforcing yarn for knitting. Impact properties of three-dimensional BWK composites both numerically and experimentally were studied by Li et al. [20]. They pointed out that energy absorption increases with the increase of impact velocity. Gude et al. [21] studied hybrid three-dimensional BWK reinforced composites for impact applications. They compared impact properties of composites with BWK preforms consisting of different fiber combinations, such as glass-glass-glass, glass-glass-aramid and glass-glass-polyethylene.

In the literature, contributions about the mechanical properties of knitted composites were reported, which were explained above. However, only a few numbers of contributions were made about the impact properties of BWK composites with various knitting combinations. Because, the fabrication method of biaxial weft knitted fabrics are comparatively very new compare to traditional knitting fabrics, it is very necessary to characterize the mechanical properties of composites with BWK fabric and with different knitting techniques. The present study investigates the three-point bending impact properties of BWK composites. The obtained results of the three-point bending impact tests can be used to design of new textile preforms during development of different composite materials.

2 Experimental Procedures

2.1 Composites Constituents

Schematic drawing of BWK fabric is shown in Fig. 1a-d. Fig. 1a depicts stitch yarns in traditional knitted fabric. The knitted fabric with weft yarn is shown in Fig. 1b. And Fig. 1c-d shows biaxial weft knitted fabric with warp, weft and stitch yarns. In our experiments, the biaxial weft knitted fabrics were used as reinforcements in the composites. In the BWK fabric, glass fiber/polypropylene (GF/PP) commingled yarns were used as warp (410 TEX), weft (410 TEX) and stitch yarns (138 TEX).

![Schematic drawings of a) knitting fiber, b) knitting+weft fiber, c) & d) biaxial weft knitted (BWK) fabric](image-url)
Five kinds of the BWK fabrics with various knitting structures were made on a flat-bed knitting machine (SHIMA SEIKI MFG., LTD., Japan). Fig. 2a-e shows the schematic drawings and photographs of the BWK fabrics (normal plain knitting, interlock, tuck, tuck-miss and interlock2).

Plain knitting is a basic knitting stitch in which each loop is drawn through other loops to the right side of the fabric (Fig. 2a).

A tuck stitch is composed of a held loop, one or more tuck loops and knitted loops. It is produced when a needle holding its loop also receives the new loop, which becomes a tuck loop because it is not intermeshed through the old loop but is tucked in behind it on the reverse side of the stitch (Fig. 2c).

A miss stitch or welt stitch or float stitch is composed of a held loop, one or more float loops and knitted loops. It is produced when a needle holding its old loop fails to receive the new yarn that passes, as a float loop, to the back of the needle and to the reverse side of the resultant stitch, joining together the two nearest needle loops knitted from it. Tuck-miss stitch was a combination of the tuck and miss stitch together (Fig. 2d).

Interlock was originally derived from rib but requires a special arrangement of needles knitting back-to-back in an alternate sequence of two sets, so that the two courses of loops show wales of face loops on each side of the fabric exactly in line with each other, thus hiding the appearance of the reverse loops (Fig. 2b and 2e) [22].

We made experiments by changing the knitting structure techniques (normal plain knitting, interlock, tuck, tuck-miss and interlock2) as shown in Fig. 2a-e. For example in the interlock2 (Fig. 2e), the straight part of loop shape in weft direction was the longest compared to other four types of knitting. Also, the loop length of interlock2 was longer than interlock. Therefore, more weft fibers could be inserted in the interlock2.

2.2 Fabrication Method

Due to vacuum-heating process of BWK preforms, good interaction between fiber and resin could be provided. Therefore, the BWK preforms were stayed in a vacuum-heater at 100°C for six hours before fabrication of composites. Ten layers BWK composites were fabricated on hot press compression machine (Fig. 3). Fig. 4a-b shows the lower and upper mold dies. The stacking sequence of ten layers composites were written in a symmetric laminate code. Fabrics were cut in the weft direction; attached in a metallic frame and put in the molding die. The molding pressure, temperature and time were 3 MPa, 220°C and 13 min. Later, mold
was cooled until it comes to the room temperature around 35°C. Fiber volume fractions were found out by performing burn-out tests.

Upper heating plate
Molding plates
Knitting preform
Lower heating plate
Press upwards

Fig.3. Molding method of BWK plate

![Fig.4. Photographs of mold die of BWK plate, a) lower, b) higher part of mold die](image)

2.3 Mechanical characterization

Fig. 5 shows the test set up and geometry of the specimen from three-point bending impact test. Three-point bending impact tests were carried out on specimens according to JIS-K7084 standard. The three-point bending impact damages were inflicted on different specimens in a drop weight test using universal testing machine type Dynatup 9250HV, Instron. The drop weight impactor was used for the tests. The weight of the impactor and the incident impact energy were 6490 g and 20 J for the three-point bending impact test. The composite coupons had a nominal dimension: 92 x 15 x 2.4-4.3 mm.

The span length was 72 mm. The three-point impact tests were conducted on specimens in the weft direction.

3 Results and Discussions

Table 1 shows the thickness and fiber volume fraction of specimens of BWK composites. The volume fractions of weft yarns in composites were increased by changing knitting yarn and interlock2 had the highest weft fiber volume fractions (18.1%). Whereas, the volume fraction of weft yarns in the plain normal BWK composites had the lowest (11%). The load-displacement curves of biaxial weft knitted composites during three-point bending impact tests are shown in Fig. 6. The interlock2 had the highest maximum load 0.8 kN, whereas normal plain had the lowest maximum load about 0.2 kN. The results of three-point bending impact tests in the weft direction are shown in Table 2. The interlock2 had the highest impact properties and total absorbed energy (15.3 J) compared to the other four specimens. After the interlock2 specimens, the tuck-miss and interlock specimens had almost same total absorbed energy which was around 10.6 J. Changing the structures of knitting makes the fabric stronger in three-point bending impact tests. Because, the density and volume fractions of weft yarn were
increased. Thus, strength of the composite and the capacity of impact shock absorption were improved. With the various knitting structure techniques, strength design in the fabric could be controlled. The interlock2 type of composites had almost four times higher maximum load and impact energy compared to the normal plain knitting (0.2 kN and 3.9 J) (Fig. 6 and Table 2). The energy result after maximum load was higher than the energy result until maximum load in all specimens. This result indicates that most of the energy was absorbed after maximum load. Further, total energy results were recalculated with same thickness of specimens and found the interlock2 absorbed more total energy (3.5 J/mm) than the other four types of composites which is shown in Table 2.

<table>
<thead>
<tr>
<th>Specimens (Composites)</th>
<th>Weft Vf (%)</th>
<th>Warp Vf (%)</th>
<th>Stitch Vf (%)</th>
<th>Total Vf (%)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>11.0</td>
<td>14.9</td>
<td>18.5</td>
<td>44.4</td>
<td>2.41</td>
</tr>
<tr>
<td>Interlock</td>
<td>15.9</td>
<td>8.9</td>
<td>16.0</td>
<td>40.9</td>
<td>3.79</td>
</tr>
<tr>
<td>Tuck</td>
<td>11.5</td>
<td>10.4</td>
<td>18.6</td>
<td>40.5</td>
<td>3.26</td>
</tr>
<tr>
<td>Tuck &amp; Miss</td>
<td>12.6</td>
<td>7.2</td>
<td>17.6</td>
<td>37.4</td>
<td>4.20</td>
</tr>
<tr>
<td>Interlock2</td>
<td>18.1</td>
<td>7.8</td>
<td>14.0</td>
<td>39.9</td>
<td>4.30</td>
</tr>
</tbody>
</table>

Table 2: Results of three-point bending impact tests by variation of different stitch techniques

<table>
<thead>
<tr>
<th>Type of knitting</th>
<th>Maximum load (kN)</th>
<th>Energy until maximum load (J)</th>
<th>Energy after maximum load (J)</th>
<th>Total absorbed energy (J)</th>
<th>Total absorbed energy/mm (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>0.23±0.0</td>
<td>1.74±0.03</td>
<td>2.26±0.01</td>
<td>3.99±0.04</td>
<td>1.66±0.02</td>
</tr>
<tr>
<td>Interlock</td>
<td>0.67±0.01</td>
<td>2.84±0.05</td>
<td>7.4±0.46</td>
<td>10.58±0.51</td>
<td>2.79±0.16</td>
</tr>
<tr>
<td>Tuck</td>
<td>0.46±0.01</td>
<td>2.51±0.05</td>
<td>4.52±0.16</td>
<td>7.03±0.46</td>
<td>2.15±0.16</td>
</tr>
<tr>
<td>Tuck-Miss</td>
<td>0.70±0.01</td>
<td>2.70±0.05</td>
<td>7.92±0.16</td>
<td>10.62±0.51</td>
<td>2.53±0.16</td>
</tr>
<tr>
<td>Interlock2</td>
<td>0.83±0.03</td>
<td>2.47±0.35</td>
<td>12.87±0.78</td>
<td>15.34±0.44</td>
<td>3.56±0.1</td>
</tr>
</tbody>
</table>

3.1 Relationship between total absorbed energy from three-point bending test and from three-point bending impact test

The relationship between the total absorbed energy from three-point bending test [23] and from the three-point bending impact test is shown in Fig. 7. The area under load-displacements curves gives the absorbed energy during the three-point bending test. Initiation energy was found out to calculate the area under load-displacement curve until maximum load and that was for propagation energy after maximum load. The total energy was the total value of the initiation and propagation energy. This graphic showed that there was a good relationship between the total absorbed energy from the three-point bending test [23] and from the three-point bending impact test. The total absorbed energy from the three-point bending test [23] increased with increasing of the total absorbed energy from the three-point bending impact test.

Besides the good relationship between both tests, the total absorbed energy from the three-point bending impact tests was much higher than that was from the three-point bending tests. Because of the good relationship between the three-point bending test and the three-point bending impact tests, the fracture
behavior of specimens during both tests could be similar.

![Graph](image)

**Fig. 7.** Total absorbed energy from three-point bending test [23] and from three-point bending impact test

### 3.2 Relationship between energy after maximum load and fiber volume fractions of composites

Relationship between energy after maximum load and fiber volume fractions of composites in the weft direction is shown in Fig. 8. Total energy after maximum load increased with increasing of volume fraction of composites in the weft direction.

![Graph](image)

**Fig. 8.** Relationship between energy after maximum load and volume fractions of composites in weft direction

Especially, in the case of two knitting techniques, such as interlock2 and tuck-miss, there was a gap which was shown in Fig. 8. We believed that this gap occurred because of effect of loop shape, which will be explained by Fig. 9a-e. Fig. 9a-e shows back face photos of the BWK fabrics with normal plain, interlock, tuck, tuck-miss and interlock2. The BWK fabric, which is shown in Fig. 9a-e, was model structure with different materials and in these materials the GF/PP commingled fibers weren’t used as warp and weft yarns. The various length of straight part of loop shape could be seen in Fig. 9a-e. The photo of the interlock2 (Fig. 9e) shows the longest length of straight part of loop shape compared to the other specimens, whereas the photo of plain knitting shows the shortest length of straight part of loop shape (Fig. 9a). The straight part of loop shape would probably contribute to increase the energy after maximum load. So, these results shows the various knitting techniques, such as interlock2, would be helpful to increase the impact absorption capacity of the composites.

![Images](image)

**Fig. 9.** Back face photos of BWK fabrics, a) normal plain, b) interlock, c) tuck, d) tuck-miss, e) interlock2
3.3 Fracture aspects of specimens after three-point bending impact test

Fig. 10a shows the normal view and Fig. 10b-c shows the enlarged view of fractured specimens after three-point bending impact test. The entire energy mechanism after the three-point bending impact tests was mainly contributed by delaminations and fiber fractures.

The fracture behaviours of specimens supported the impact test results. The highest numbers of fiber fractures were seen in the center of the interlock2 specimen (the highest impact properties). It was also seen some delaminations in the interlock2. The lowest numbers of fiber fractures were seen in the center of plain specimen (the lowest impact properties). It couldn’t be seen any delaminations on the surface of the plain specimen.

4 Conclusions

The BWK fabrics on SHIMA SEIKI knitting machine were constructed by the warp, weft and knitted stitch yarns. This fabric offers wide variation of designs in the industries, which woven fabric and uni-directional material cannot do it. In the production site, changing yarn is much easier on SHIMA SEIKI knitting machines compared to other textile machines. Our study showed that the impact properties of composites could be improved by changing knitting techniques. With its proprietary technique, the minimization of the production time in the process of layering, the reduction of the cut-loss and total production cost, easiness in the strength design can be achieved for the BWK fabrics. The interlock2 had the highest impact properties, such as maximum load and total absorbed energy, compared to the other four specimens. The good agreements between the total
absorbed energy from three-point bending test [23] and from three-point bending impact test supported our test results. The relationship between energy after maximum load and volume fractions of composites in the weft direction was also studied and it was found that the total energy after maximum load increased with increasing of the volume fraction of composites in the weft direction. The fracture aspects of specimens after three-point bending impact test were also investigated and the fracture behaviours of specimens supported the three-point bending impact test results. In future study, we will try to fabricate 3-D BWK composites by using WHOLE GARMENT® technology which is available on SHIMA SEIKI weft knitting machines.

References


