MECHANICAL CHARACTERIZATION OF NONWOVEN COMPOSITES WITH PET HOLLOW FIBERS AND ELASTOMERIC FIBERS FOR CUSHION MATERIALS

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1 Introduction
Nonwovens are expanding the importance in technical textiles; in particular, the automotive industry is the largest sector of technical nonwovens, which are widely used in many forms for interiors and structural components for the noise, vibration and harshness (NVH) performance and weight reduction [1]. In fact, nonwovens are widely used in the automotive industry due to their excellent characteristics such as light weight, sound and vibration insulation, flexibility, versatility and easy tailored properties, moldability, recyclability, low material and processing costs [2]. About forty automotive parts or components are made of nonwovens in various forms, such as oil and air filters, headliner, insulator dash/hood, floor mat/carpet, door/side trim, rear package tray, etc [3].

Polyurethane (PU) foams are still the preferred material for automotive seat cushion construction. However, some deficiencies of PU foams have been recognized in difficult recycling and toxic gas release during their manufacturing processes. The recognition of such concerns has led to new concept, namely, “textile foams” to replace the PU foams with textile nonwoven structures. The advantages of textile foams include reduced fogging and unwanted odors, environmental-friendly laminating process, surface material uniformity, possibility of using reclaimed fibers, and recycling into reclaimed or recycled fibers [3].

In this study, our efforts are made to understand the textile nonwoven composites, produced by the carding web formation process using hollow polyester fibers and elastomeric binder fibers to fully realize the greater potential for cushion materials to replace PU foams. Effects of needle punching (NP), thermal bonding (TB) and/or through-air bonding (TA) are explored in terms of the physical and mechanical properties of nonwovens by the establishment of the relationship between the bonding processes and nonwoven characteristics such as hardness and support factors.

Furthermore, the thermoformability of nonwovens is investigated to assess forming processability of initial planar material into a three dimensional shape for stamp forming processes such as deep drawing (cylinder and hemisphere), V-bending, and matched-die dome forming. Effects of forming temperatures and forming shape are studied in terms of shape conformance and forming limits.

2 Experimental
2.1 Materials
The commercial grade PET hollow fibers were used in this study for main matrix fibers, and the fibers were supplied by Woongjin Chemical, South Korea with 7 denier, 64 mm length, 4.1 g/den tenacity, and 29.7 % hollowness. The ELK® fibers (Teijin, Japan) were used for binder fibers, having a heat fusible polymer at a lower-melting temperature. The fibers are eccentric sheath/core type fibers of low-melting elastomeric copolyester and polyester with 5 denier and 64 mm length. The characteristics and properties of the fibers used are listed in Table 1, and the cross sections of the fibers are shown in Fig. 1.

For comparison, flexible molded polyurethane (PU) foams were taken from a front driver seat in a Hyundai Grandeur TG model. The PU foam was found to have an open-cell microstructure and density of 37.8 kg/m³. The microstructure is shown...
in Fig. 2, exhibiting the average cell diameter of 141 μm, strut thickness of 40 μm, and 650 pores/mm².

2.2 Nonwoven manufacture

Nonwovens were manufactured using a pilot scale nonwoven carding machine at the Korea Institute of Industrial Technology. The hollow and binder fibers were mixed at a weight ratio of 8:2, opened and carded for the web formation. The carded web was laid by a cross lapper to produce the nonwoven webs with 300 g/m² and 10 mm thickness. The resultant webs were post-processed and bonded by only a thermal bonding (TB) process, needle punching and thermal bonding (NP+TB) or needle punching and through-air bonding (NP+TA) combined processes. The webs were needle punched at a punching rate of 170 strokes/min and/or thermal bonded by a double belt press at 170 °C at a feeding speed of 2 m/min. Alternatively, the needle-punched webs were bonded by hot air blowing in a through-air bonding chamber at 180 °C at a conveying speed of 4 m/min for 90 seconds. Fig. 3 shows the manufacturing processes and sample identification in terms of bonding processes.

2.3 Test methods

The thickness of nonwovens was measured at a compressive load of 0.5 gf/cm² using KES-FB3 (Kato Tech, Japan). The density was calculated based on the geometry of nonwovens and the area density. Air permeability was evaluated by TEXTEST FX 3300 at a differential pressure of 125 MPa. Air permeability can be expressed as the rate of air flow through a fixed fabric area per second.

For tensile tests, the nonwovens were cut into the standard tensile specimens with the dimension of 5 cm × 25 cm (width × length) in accordance to KS M ISO 9073-3. The test gauge length is 150 mm, and the tensile tests were performed with an Instron 3340 at a cross head speed of 10 mm/min. For each specimen type, at least five specimens were tested in the machine direction (MD) and the cross direction (CD).

Hardness measurement for nonwovens was carried out in accordance with KS M ISO 6672 with a universal testing machine (Tinius Olsen, England). The nonwovens were cut into the size of 5 cm × 5 cm (width × length). The 5 layers of nonwovens were laid up and compressed at a constant speed 10 mm/min using a circular pressure foot with 100 mm diameter. The hardness was determined as a measured load when the thickness was deformed to 30 % of their original thickness. The hysteresis was calculated by Equation 1 from the load-displacement curves during the hardness test.

\[
\text{Hysteresis} \% = \frac{A_{\text{loading}} - A_{\text{unloading}}}{A_{\text{loading}}} \times 100 \tag{1}
\]

where \(A_{\text{loading}}\) is the area under the load-displacement curve on loading, and \(A_{\text{unloading}}\) is the area under the load-displacement curve on unloading.

Permanent shrinkage (PS) or compression sets for nonwovens was the degree of permanent deformation in accordance with KS M ISO 6672. The nonwovens were cut to the size of 5 cm × 5 cm (width × length) and the 5 layers were stacked to satisfy the minimum thickness requirement of 5 cm. The original thickness \((T)\) of the stacked sample was measured first. The nonwoven was pressed to 50 % of the original thickness using a thick aluminum plate fixture, and then placed in a convection oven at 70 °C for 22 hours. The aged samples were removed from the oven and placed for 30 minutes at a standard condition of 20 °C and 56 % RH with the removal of the fixture. The final thickness \((T_f)\) was measured, and the permanent shrinkage was calculated by the following equation.

\[
\text{PS} \% = \frac{T - T_f}{T} \times 100 \tag{2}
\]

The formability tests were performed using an environmental chamber on the universal testing machine at 80, 150, and 200 °C through the modified California bearing ratio (CBR) plunger method, V-bend, and the matched die dome stamping methods.

The CBR plunger method for measuring the burst strength for geotextiles was modified to simulate the deep drawing of nonwovens [4]. The cylindrical and hemispherical plungers were used to assess the effects of a different shape/surface area on the formability properties. The dimensions of the test
The thickness, area density, density, and air permeability of nonwovens are summarized in Table 2. The thickness and area density show around 20% and 5% variations from the processing set values of 10 mm and 300 g/m², respectively, due to unknown parameters such as fiber properties and manufacturing conditions. The thickness of NP+TB nonwovens is slightly lower than that of TB and NP+TA nonwovens because the combined needle punching and thermal bonding processes result in fiber entanglements and compression through the thickness direction of the webs, respectively, leading to the denser fabric structures. On the other hand, the NP+TA nonwovens show the highest bulkiness due to the ability of through-air thermal bonding without the physical web contact and compression.

The relationship between the density and air permeability in Table 2 demonstrates that the NP+TA nonwovens have the slightly higher air permeability than the other nonwovens due to their bulky structures. It is usually observed that air permeability increases nonlinearly as thickness and area density decrease, and the area density has a more significant influence on air permeability than either thickness or fiber size [5]. Compared to the PU foam, the higher permeability and lightness for the nonwovens demonstrates seating comfort with fresh sensation and lightness for seat cushioning pads.

Effects of bonding processes on the tensile properties of bonded nonwovens are clearly demonstrated by the load-displacement curves of nonwovens in Fig. 9, although all the nonwovens have a comparable thickness and area density. For the machine direction (MD), the nonwoven strength is significantly affected by the bonding processes. The NP+TA nonwoven, bonded by the combination of the needle punching and through-air bonding, shows the remarkably higher tensile peak load than the nonwovens bonded by the other bonding processes. The only thermal bonded nonwoven (TB) has the similar strength to the NP+TB nonwoven but the lower elongation in comparison with the NP+TB and NP+TA nonwovens. The needle punched and through-air bonded nonwoven has the better performance than the other bonded nonwovens in terms of strength and elongation. The higher strength and elongation can be attributed to the fiber entanglements through the needle punching process,
and better consolidated structures due to more thermally bonded inter-fiber conjunctions via the through-air bonding process. The tensile peak load in the cross direction (CD) exhibits the lower value for all tested samples than in the MD direction. The significant drops of the peak load in the CD direction are in good agreement with those reported in the literature [6] due to more aligned fibers in the MD direction by the main cylinders and the workers in carding processes.

Hardness is the resistance of materials to deformation under an applied force, which is one of important test parameters to determine seating comfort or discomfort. The load-compressive ratio curves for the PU foam and nonwovens in the hardness tests are shown in Fig. 10. The typical curve of PU foams exhibits three distinct regions: linear elastic region, plateau region and densification (hardening) region [7]. The PU foam has the higher load than the nonwovens in the elastic region. However, the load reaches the plateau value while the load for the nonwovens sharply increases. Finally, the hardness of the PU foam, measured by the indentation force deflection (IFD) at a compressive ratio of 70%, is lower than that of all the nonwovens (Table 3). The NP+TA nonwoven shows the highest softness with the lowest maximum load among the other nonwovens due to its bulkiness, and the nonwoven is similar to the PU foam. It is worthy to note that the additional needle punching processes increases hardness for nonwovens due to denser fabric structures, and the incorporation of through-air bonding process into nonwovens increases the softness and bulkiness by maintaining the web thickness.

A support factor or sag, defined by the ratio between 65 % IFD and 25 % IFD, is one of the most important characteristics of foams because it governs comfort and durability. The definition of support is the ability to hold up the weight of a person. Good supportive foams do not “bottom out” or compress to a point where they no longer hold up the weight of the person, and also are capable of distributing the weight of the person. Typical PU foams have the support factor ranging from 1.8 to 3.0. The higher the number is, the greater the foam's ability is to provide support. The support factor of the PU foam in Table 3 has the value of 2.8. The 2.8 or higher values are regarded as providing good comfort. If the cushioning material has a higher initial collapse stress (25 % IFD), the factor is likely to be low and the seat may be uncomfortable. The higher support factors for the nonwovens demonstrate greater potential for comfort cushioning materials.

The permanent shrinkage (PS) indicates the irreversible deflection after exposure to 70 °C for 22 hours. Table 3 shows that the foam has the lower permanent shrinkage compared to all the nonwovens. The higher permanent shrinkage for the nonwovens implies the inferior thickness recovery after compressive deflection, which may be problematic in durability for cushioning materials such as the service-in thickness reduction and hardness change. With regarding to the effects of bonding processes on the nonwovens, the NP+TA shows the higher permanent shrinkage than the other nonwovens. It is believed that although fiber entanglement and secure fiber bonding can be induced via needle punching and through-air bonding, the bulkiness and softness will deteriorate the thickness recovery and the resistance to compressive forces.

Fig. 11 shows the typical load-displacement curves of TB nonwovens as a function of temperature with cylindrical and hemispherical plungers for the modified CBR tests. It can be seen that the forming load is much higher for the hemispherical plunger than that for the cylindrical plunger due to the larger forming surface. As the forming temperature increases, the curves show more flexible with the lower maximum load and greater displacement. As an example, Fig.12 shows formed nonwovens under different temperatures after the CBR tests. At the lower temperatures, it is shown that the deformation area is limited to the contact surface. However, with increasing temperature to 200 °C, the whole surface was deformed to accommodate the large deformation. It can be concluded that the temperature above 150 °C can facilitate the forming process.

Fig.13 shows the photographs of TB nonwovens after V-bending at different temperatures. For single curvature V-bending, formability can be assessed in terms of shape conformance and the quality of the bend region [8]. The angle deviation depends on whether the specimen spring back or forward. If the part angle actually deformed is less than 90°, this
phenomenon is called ‘spring-forward’ effect. If the part angle actually deformed is larger than 90°, this phenomenon is called ‘spring-back’ effect. At the lower temperature, all the specimens show the spring back effects due to simple contraction and the residual elastic stress during the forming process and relaxation on demolding. For the successful forming, the temperature should be maintained above 150 °C.

The typical load-displacement curves of the nonwoven are shown in Fig. 14 for the matched die dome forming at different temperatures. The curves are similar to those for the CBR tests, demonstrating more flexibility with the lower maximum load and greater displacement with increasing the forming temperature. Fig. 15 shows that the nonwoven can be successfully thermoformed only at 200 °C in terms of shape conformity. For the lower temperatures after complete forming, the dome collapsed and thickness increased because the binder fibers cannot facilitate fusion and flow to form the solid bonding for dimensional stability on being removed from the die.

4 Conclusions

The experimental results showed that the bonding processes significantly affect the mechanical properties for the nonwovens, implying the greater design flexibility to satisfy the variety of performance requirements for the automotive industry. The higher tensile strength and elongation were attributed to the fiber entanglements and better consolidated structures through the combined needle punching and through-air bonding processes. However, the bulky structure was found to decrease the hardness and support factor along with the increased permanent shrinkage. Compared with the PU foam, the nonwoven showed firmness but higher support factor, leading to a high level of performances, e.g. good seating comfort.

The thermoforming study on TB nonwovens found that the forming temperature was above 150 °C for shape conformity and easy thermoforming processes.

Table 1 Physical and mechanical properties of PET hollow and elastomeric binder fibers

<table>
<thead>
<tr>
<th>Sample</th>
<th>PET hollow fibers</th>
<th>Binder fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denier</td>
<td>7 denier</td>
<td>5 denier</td>
</tr>
<tr>
<td>Length</td>
<td>64 mm</td>
<td>64 mm</td>
</tr>
<tr>
<td>Tenacity</td>
<td>4.1 g/den</td>
<td>2.5 g/den</td>
</tr>
<tr>
<td>Elongation</td>
<td>38.1 %</td>
<td>80.5 %</td>
</tr>
<tr>
<td>Feature</td>
<td>Hollowness of</td>
<td>Eccentric</td>
</tr>
<tr>
<td></td>
<td>29.7 %</td>
<td>sheath/core</td>
</tr>
</tbody>
</table>

Table 2 Physical properties of PU foams and nonwovens

<table>
<thead>
<tr>
<th>Sample</th>
<th>Thickness [mm]</th>
<th>Area density [g/m²]</th>
<th>Density [kg/m³]</th>
<th>Air permeability [cm/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PU</td>
<td>9.0</td>
<td>340.0</td>
<td>37.8</td>
<td>89.8</td>
</tr>
<tr>
<td>TB</td>
<td>10.1</td>
<td>302.4</td>
<td>29.9</td>
<td>178.8</td>
</tr>
<tr>
<td>NP+TB</td>
<td>9.0</td>
<td>316.4</td>
<td>35.2</td>
<td>161.0</td>
</tr>
<tr>
<td>NP+TA</td>
<td>12.2</td>
<td>298.9</td>
<td>24.5</td>
<td>180.4</td>
</tr>
</tbody>
</table>

Table 3 Mechanical properties and permanent shrinkage of PU foams and nonwovens

<table>
<thead>
<tr>
<th>Sample</th>
<th>Hardness [N]</th>
<th>Support factor</th>
<th>Hysteresis [%]</th>
<th>PS [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PU foam</td>
<td>20.1</td>
<td>2.8</td>
<td>37.9</td>
<td>25.0</td>
</tr>
<tr>
<td>TB</td>
<td>38.8</td>
<td>11.0</td>
<td>40.3</td>
<td>29.1</td>
</tr>
<tr>
<td>NP+TB</td>
<td>76.0</td>
<td>14.8</td>
<td>46.4</td>
<td>27.2</td>
</tr>
<tr>
<td>NP+TA</td>
<td>26.0</td>
<td>7.7</td>
<td>50.7</td>
<td>32.8</td>
</tr>
</tbody>
</table>

Fig. 1. Cross-sections of fibers; (a) hollow PET fibers and (b) elastomeric sheath/core binder fibers.
Fig. 2. Microstructures of PU foams.

Fig. 3. Schematic of manufacturing processes for nonwoven composites.

Fig. 4. Experimental setups for CBR forming tests.

Fig. 5. Experimental setups for stamp forming; (a) V-bending and (b) matched die dome forming.

Fig. 6. Forming plunger and female mold for V-bending.

Fig. 7. Forming plunger and female mold for matched die dome forming.
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Fig. 8. SEM micrographs of nonwoven surfaces; (a) TB, (b) NP+TB and (c) NP+TA.

Fig. 9. Tensile load-displacement curves of nonwovens; (a) machine direction and (b) cross direction.

Fig. 9. Cont.

Fig. 10. Typical load-compressive ratio curves of PU foam and nonwovens during hardness tests.

Fig. 11. Typical load-displacement curves of TB nonwovens at different temperatures for CBR tests; (a) cylindrical and (b) hemispherical plungers.
Fig. 11. Cont.

Fig. 12. Photographs of formed nonwovens after CBR tests.

Fig. 13. Photographs and shape conformity formed nonwovens after V-bending.

Fig. 14. Typical load-displacement curves of nonwovens at different temperatures for matched die dome forming.

Fig. 15. Photographs and shape conformity of formed nonwovens after matched die dome forming.

References


