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 the last decades, the automotive industry has achieved significant progress in reducing vehicle weight through the development of new vehicle structural design and the utilization of lightweight materials for fuel economy and emission gas reduction. In addition, great efforts have been made on the NVH management to improve vehicle interior quietness and comfort. The car interior plays a significantly important role in aesthetics, sound and vibration insulations, which can be economically and functionally improved by the use of textile materials [2]. 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 [3]. 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 [4].

Polyurethane (PU) foams are still the preferred material for automotive seat cushion construction [5]. 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, environmentally-friendly laminating process, surface material uniformity, possibility of using reclaimed fibers, and recycling into reclaimed or recycled fibers [3].

In the last decade, the elastomeric polyester fibers, namely ELK® fibers, have been successfully introduced by Teijin, Japan to replace PU foams in upholstery structures for public transport vehicles like trains, subways and more recently for airplane seats [6]. However, to the authors’ knowledge, the nonwovens, comprising of the elastomeric fibers, are limited to the open literature, especially with respect to seat cushioning performances. In this study, our efforts are made to understand the textile nonwoven foams, 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. The hollow fibers have a continuous hole running down the middle, which can provide greater bulkiness,
compression resilience and lightness with nonwoven fabrics to substitute PU foams in the automotive industry [7,8]. Effects of bonding processes such as 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 tension, hardness, compression and ball rebound resilience.

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 method

Single fiber testing was performed through Favimat-Robot (Textechno, Germany) to analyze the tensile properties and linear density (fineness) of the fibers. The linear density was measured by the vibroscopic method, and tensile tests were carried out using a gauge length of 20 mm at a crosshead speed of 10 mm/min with a pretension of 0.5 cN/dtex.

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 100 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 (Tinus 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.

\[ \text{Hysteresis} \% = \frac{A_{\text{loading}} - A_{\text{unloading}}}{A_{\text{loading}}} \]  

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.

Compressive properties of nonwovens are evaluated by KES-FB3. The nonwoven was compressed by a 2 cm \(^2\) pressure foot at a compressive deformation rate of 20 \( \mu \)m/sec. Three parameters of linearity (LC), compressive energy (WC), and resilience (RC) were calculated by Equation 2-4 [9].

\[ LC = \int_0^{E_m} F dE / (0.5F_m E_a) \]  
\[ WC = \frac{1}{A} \int_0^{E_m} F dE \]  
\[ RC [\%] = \frac{\int_0^{E_r} F' dE / \int_0^{E_m} F dE}{} \times 100 \]  

where \( A \) is the compressive area (2 cm\(^2\)), \( F_m \) is the maximum compressive load, \( F \) denotes the force during loading and \( F' \) denotes the force during unloading. \( E_a \) is the extension at \( F_m \) and \( E_r \) is the extension after the load is returned to zero.

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 (\( T_1 \)) was measured, and the permanent shrinkage was calculated by the following equation.

\[ PS [\%] = \frac{T - T_1}{T} \times 100 \]  

Ball rebound tests were carried out in accordance with KS M ISO 8307. A 16.8 g steel ball with 16 mm diameter was dropped from a height of 516 mm onto the 5 layered nonwovens. The rebound height was measured and corresponded to ball rebound resilience as a percentage of the original height.

3. Results and discussion

3.1 Nonwoven morphology and properties

Fig. 4 shows the SEM micrographs to illustrate the surface morphology of the nonwovens with bonding structures between the hollow fibers and binder fibers. The larger diameter hollow fibers are randomly distributed, and the smaller diameter low-melting binder fibers fuse and flow over the hollow matrix fibers, leading to fiber conjunction and bonding at their crossover areas. However, the SEM micrographs do not reveal distinct
bonding structures between the different bonding processes.

The area density, thickness and air permeability of nonwovens are summarized in Table 2. The area density and thickness show around 5 % to 20 % variations from the processing set values of 300 g/m² and 10 mm, 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 [10]. 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. 5, 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 [11] due to more aligned fibers in the MD direction by the main cylinders and the workers in carding processes.

**Table 2** Physical properties of PU foams and nonwovens.

<table>
<thead>
<tr>
<th></th>
<th>Area density [g/m²]</th>
<th>Thickness [mm]</th>
<th>Density [kg/m³]</th>
<th>Air permeability [cm³/cm²/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PU Foam</td>
<td>340.0</td>
<td>9.0</td>
<td>37.8</td>
<td>89.8</td>
</tr>
<tr>
<td>TB</td>
<td>302.4</td>
<td>10.1</td>
<td>29.9</td>
<td>178.8</td>
</tr>
<tr>
<td>NP+TB</td>
<td>316.4</td>
<td>9.0</td>
<td>35.2</td>
<td>161.0</td>
</tr>
<tr>
<td>NP+TA</td>
<td>298.9</td>
<td>12.2</td>
<td>24.5</td>
<td>180.4</td>
</tr>
</tbody>
</table>

**Fig. 4** SEM micrographs of nonwovens: (a) TB, (b) NP+TB and (c) NP+TA.
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. 6. The typical curve of PU foams exhibits three distinct regions: linear elastic region, plateau region and densification (hardening) region [12]. 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 [13]. 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 [14]. The higher the number is, the greater the foam’s ability is to provide support. The support factor of the PU foam show in Table 3 has the value of 2.8. The 2.8 or higher values are regarded as providing good comfort [15]. If the cushioning material has a higher initial collapse stress, 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 4 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, 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.

The compression behavior for the PU foam and the nonwovens is depicted in Fig. 7. Three parameters of linearity (LC), energy (WC), and resilience (RC) of compression are tabulated in Table 4. The LC indicates the linear response in the load-displacement curve in compression. The nonwovens show the lower LC and
WC than those of the PU foam, indicating that the nonwovens are more compressible and flexible. The compression resilience is the ability to return to the original thickness after compression. The nonwovens, except NP+TA, are more resilient than the PU foam. The resilient nonwovens will present better performances with seating comfort and softness for seating pads. The only thermal bonded nonwoven (TB) shows the larger RC than NP+TB and NP+TA, that is contrary to the previous report [16]. The needle punching bonding process for nonwovens results in better consolidation and more fiber entanglement, reducing the fiber-to-fiber slippage during compression and improving the compression resilience. Although the contrary results cannot be clearly verified in this study, the possible explanation may be associated with the collapsing of through-thickness oriented fibers.

![Fig. 7 Typical compressive load-extension curves of PU foam and nonwovens by KES-FB3.](image)

**Table 4** Compressive properties by KES-FB3 and permanent shrinkage (PS) of PU foams and nonwovens.

<table>
<thead>
<tr>
<th></th>
<th>LC (g/f/cm²)</th>
<th>WC (%)</th>
<th>RC (%)</th>
<th>PS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PU Foam</td>
<td>1.4</td>
<td>20.4</td>
<td>59.8</td>
<td>25.0</td>
</tr>
<tr>
<td>TB</td>
<td>0.7</td>
<td>9.9</td>
<td>68.1</td>
<td>29.1</td>
</tr>
<tr>
<td>NP+TB</td>
<td>0.6</td>
<td>7.1</td>
<td>61.7</td>
<td>27.2</td>
</tr>
<tr>
<td>NP+TA</td>
<td>0.7</td>
<td>11.3</td>
<td>53.1</td>
<td>32.8</td>
</tr>
</tbody>
</table>

![Fig. 6 Typical load-compressive ratio curves of PU foam and nonwovens during hardness tests; (a) PU foam, (b) TB, (c) NP+TB and (d) NP+TA.](image)

![Fig. 8 Ball bound height and resilience of PU foam and nonwovens.](image)
through the needle punching process and then the loss in the recovery to the original thickness after compression.

The test results for ball rebound tests are shown in Fig. 8. The rebound height and resilience for TB and NP+TB nonwovens show the slightly higher values than the PU foam. The rebound resilience shows the similar trend to the compression resilience measured by KES-FB3. The potential energy of a ball is transferred into the cushioning materials upon impact. The energy is absorbed partially by the materials and the remaining energy is transferred back to the ball rebound. The low rebound height indicates high energy absorption materials, and thus the ball rebound height shows a good correlation with compression resilience. The previous study shows that the ball rebound resilience was found to increase with decreasing hysteresis loss. However, the relationship was not sufficiently quantitative since the ball rebound energy was less than that predicted from the stored energy [17].

The lowest ball rebound resilient NP+TA nonwoven can be explained by the bulky fibrous structure, being responsible to facilitate the energy loss mechanisms such as reorientation and friction between fibers.

4. Conclusions

The seating comfort performance of elastic textile nonwoven foams were evaluated through the assessment of tensile properties, hardness, compression properties and ball rebound resilience with regard to effects of bonding processes. The study demonstrated the greater potential of the nonwovens for cushion materials, which exhibited the excellent properties and were comparable to the PU foam.

The experimental results showed that the bonding processes significantly affected 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 compressive and ball rebound resilience. The hardness, support factor, compressive and ball rebound resilience were found to be the important test parameters to determine seating comfort although the correlation between the cushioning characteristics and seat comfort was difficult to determine qualitatively because seat comfort was extensively dependent on occupant preferences. Compared with the PU foam, the nonwoven showed firmness but higher support factor, leading to high level of performances, e.g. good seating comfort. The results of compressive and ball rebound resilience indicated that the nonwovens were more resilient and comfortable than the PU foam with the better air permeability.

References