

## PAPER

## ENGINEERING SCIENCES

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# Fabrication of Compound Nonwoven Materials for Soft Body Armor\*

**ABSTRACT:** The primary objective of body armor research is the development of low-cost, lightweight, wearable garments that effectively resist ballistic impact. This study introduces a material intended to reduce nonpenetration trauma by absorbing energy from ballistic impacts. Layers of web were made by low-melting point polyester (LMPET) on unaligned fibers of high-strength polyamide 6 (HSPA6). A compound nonwoven fabric was made by laying high-strength Vectran filaments between two layers of HSPA6-LMPET web. The new fabric underwent needle punching and thermal bonding to form a composite sandwich structure. The new fabric was subjected to a falling weight impact test and a ballistic impact test. The results indicated that the material with the new design reduced maximum indentation depth by 8%. Furthermore, soft body armor made from the material with the new design would cost less to produce and would weigh 22.5% less than conventional soft body armor.

**KEYWORDS:** forensic science, compound nonwoven fabric, bulletproof, ballistic impact, energy absorption, falling weight impact

Early ballistic vests used materials such as cotton, silk, and steel; later improvements were because of the introduction of materials such as fiberglass, ceramics, and Kevlar. Synthetic polymeric fibers have made it possible for a lightweight, flexible vest to exhibit more ballistic resistance than a twentieth-century flak jacket. For many years, new materials have caused body armor to improve in comfort, efficiency, durability, and reliability. Textile armor materials include aramid fibers, highly oriented ultrahigh molecular weight polyethylene (UHMWPE), and p-phenylene-2-6-benzobisoxazole (PBO) and polyamide (PA) (1,2).

A projectile that strikes textile armor transfers energy that spreads as a wave. The velocity of wave propagation is directly proportional to the square root of Young's modulus and inversely proportional to the square root of the fiber density. Transverse and longitudinal wave (direction perpendicular to the fibers and parallel to the fibers, respectively) propagations have common physical characteristics, although transverse propagations are more directly related to local deformation and penetration during the ballistic event. Both the projectile and the armor undergo deformation and friction. The projectile's geometry and velocity determine the deformation of the armor's layers (3–7).

Studies of bullets with speeds between 350 and 430 m/sec suggest that nonwoven fabric facing on a woven fabric can provide better protection than a spectra polyethylene shield alone (8). Another study showed that when armor has sufficient strength,

armor deformation within a large impact area can help the armor absorb energy (9). Provided with appropriate processing conditions, the structure of compound nonwoven fabric could have a better cushion effect. In the context of the aforementioned papers and of other pre-existing literature (10–15), this research sought to determine whether a particular new nonwoven fabric can be used to make useful ballistic armor.

A vest composed only a few layers of Kevlar® will stop projectiles but transmit nonpenetration traumas to the wearer; the Kevlar® vest many centimeters thick would prevent nonpenetration traumas but would also prohibitively limit the wearer's movements. This research presents a new nonwoven material that can prevent nonpenetration traumas if it is used as a cushion within a thin vest.

The textile industry has made great strides by introducing complex compound fabrics with new dynamical and mechanical properties. Many compound fabrics use reinforcement; the present research uses a fabric reinforced by filaments and bonded by needle punching and thermal bonding. Filaments were laid between two nonwoven layers; the combined filaments and layers formed a sandwich structure. The sandwich structure was bonded to complete the compound fabric. Bonding points can create vulnerabilities in many armor designs, but compound fabrics might reduce the disadvantages created by bonding points. Furthermore, needle-punched compound fabrics could be strengthened if their layers were joined by fibers or continuous loops. Such armor could disperse mechanical strain and increase resistance to ballistic impacts.

### Theory of Force Dispersion in a Soft Bulletproof Vest

In the context of protection engineering, impact is a phenomenon characterized by a high loading in a short time. Strain wave theory is the most appropriate model for the mechanics of a ballistic vest stopping a bullet; strain waves behave differently, depending on whether the armor is made from unidirectional materials, woven materials, or nonwoven materials, respectively.

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Woven fabrics have the most bonding points. A bullet that strikes woven armor transfers energy to a few fibers, but those few fibers interact with many nearby fibers because of the many bonding points; thus, woven armor tends to spread energy over a wide area. However, bonding points also act as fixed ends. If the reflection waves formed by the fixed ends overlap the original incident waves, the yarns of the armor will endure greater tensile stress. If the breaking strength of any yarn is exceeded, that yarn will break. Woven fabrics often resist penetration by large, blunt bullets but are penetrated by small, sharp projectiles (such as flechettes or shrapnel fragments) that can push aside single yarns. Increasing the fabric density within a certain area should reduce the penetration problem and heighten fabric strength. However, it could also reinforce the negative effects of reflective overlap by strain waves.

Unidirectional fabrics do not have the fixed-end problems or the penetration problems seen in woven fabrics, because unidirectional fabrics are composed of parallel fibers bonded with thermoplastic resin. Energy from an impact is absorbed by the elongation and breakage of the fibers which are at or near the impact point. Unidirectional fabrics maintain the original strength of the fibers and rapidly disperse the energy to a larger area. Thus, bullet-resistant vests can be made from several layers of unidirectional fabrics (5). Based on their structures, materials have different energy-absorption capabilities. For ordinary materials, hard ones have lower extension and energy-absorption capability. Thus, when choosing the materials for bulletproof vest, we need to consider energy-dispersion speed as well as energy-absorption capability, in particular materials with high Young's modulus and low density are the best option. The stages of protection structure are developed from the plain structure, knitted structure, and unidirectional (UD) structure to nonwoven structure. Currently, bulletproof materials are mainly Kevlar<sup>®</sup> and UHMWPE, and fabric organization is mainly plain structure and UD structure (16).

The dynamic response of a single fiber or a bundle of fibers to ballistic impact can be divided into five stages (17):

- The projectile trajectory is assumed to be perpendicular to a flat slab of armor, the fiber is parallel to the surface of the armor slab, the slab can be considered "horizontal", and the trajectory can be considered "vertical" (see Fig. 1). The vertical displacement of the fiber causes a longitudinal wave to move outward. If the longitudinal wave moves fast, the fiber volume will be increased because of the fibrous deformation caused by interaction with the bullet.
- The impact causes a tensile strain of magnitude proportionate to projectile velocity. The material starts inward compression from the area of impact.

$$\varepsilon = V/C \quad C = \sqrt{E/\rho}$$

V is the bullet's velocity (m/sec); C is the the transmission speed of the strain wave inside the fiber; E is the Young's

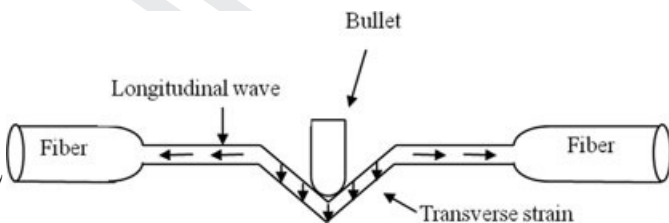


FIG. 1—The energy dispersion and tensile strength degradation of a single fiber struck by a bullet.

modulus for the fiber;  $\rho$  is the fiber density ( $\text{g}/\text{cm}^3$ );  $\varepsilon$  is the fibrous instantaneous strain

- The bullet impact causes a transverse strain. The transverse strain moves outward at a transmission speed that depends on the bullet's velocity.
- The strength is limited by the fiber's tensile strength.
- All energy that is absorbed after the fiber generates the longitudinal wave decreases the fiber's tensile strength.

## Materials and Methods

### Materials

Layers of nonwoven fabric were made as follows: HSPA6 fibers (fiber linear mass density: 6 deniers; fiber length: 64 mm) and LMPET fibers (fiber linear mass density: 4 deniers; fiber length: 51 mm; melting point:  $110^\circ\text{C}$ ) were blended at the weight ratio of LMPET (10 wt%). The blended fibers were opened, re-blended, and formed into fiber webs. Heat was applied to melt the LMPET fibers. The area density of the nonwoven fabric was  $200 \text{ g}/\text{m}^2$ .

Each batch of the new test material was made as follows: First, the density of internal filaments was specified at 100, 200, 300, 400, or 500 g of filaments per square meter. Vectran filaments with linear mass density of 1000 deniers were arranged to occupy the specified density per square meter and then were laid on one layer of nonwoven fabric, and another layer of nonwoven fabric was laid over the filaments. Each piece of test material comprised a sandwich structure, with two layers of HSPA6 nonwoven fabrics enclosing a layer of Vectran filaments. Then the sandwich was punched with rough needles that entangled the fibers of different layers. Finally, the sandwich was thermally treated, which caused LMPET fibers to melt further and bond with the needle-punched bonds, and this prevented the Vectran fibers from sliding freely within the sandwich. The end product was nonwoven fabric. There were five varieties of nonwoven fabric, called 100V, 200V, 300V, 400V, and 500V; the number stood for the filament area density, and the "V" abbreviated "Vectran." One hundred pieces of the new material were made as described earlier, with twenty pieces for each of 100, 200, 300, 400, and 500 g of filaments per square meter. For each density, 10 pieces were 30 cm by 30 cm and 10 pieces were 10 cm by 10 cm.

The larger pieces of nonwoven material were combined with Kevlar<sup>®</sup> unidirectional (UD) fabrics to make square slabs of fabric armor. Each piece of test armor was a square slab, consisting of 28 layers of Kevlar<sup>®</sup> UD fabrics enclosing the test material. The grain of each Kevlar<sup>®</sup> UD fabric layer was perpendicular to the grain of adjacent layers, and our new nonwoven material was between the fourth and fifth Kevlar<sup>®</sup> UD fabric layers. These five varieties of new armor were called 100V + 28UD, 200V + 28UD, 300V + 28UD, 400V + 28UD, and 500V + 28UD. The "UD" abbreviates "unidirectional."

### Target Preparation

Figure 2 is a schematic diagram of the new armor target. The exemplar commercial vest (Rabintex Industries, Ltd., Israel) was denoted "44UD and 6-ply. Kevlar<sup>®</sup>" because it used 44 layers of unidirectional fabrics to enclose a six-layer cushion. It was used as a basis for comparison. The vest contained an inner cushion layer made of 6-ply Kevlar<sup>®</sup>; the cushion was a sandwich made of two

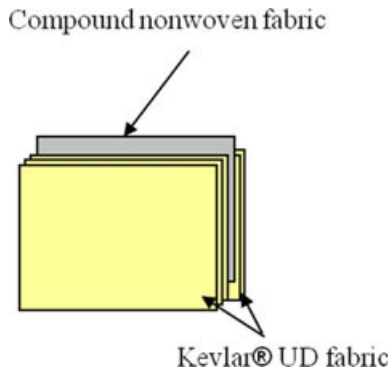


FIG. 2—Schematic diagram of a new armor target.

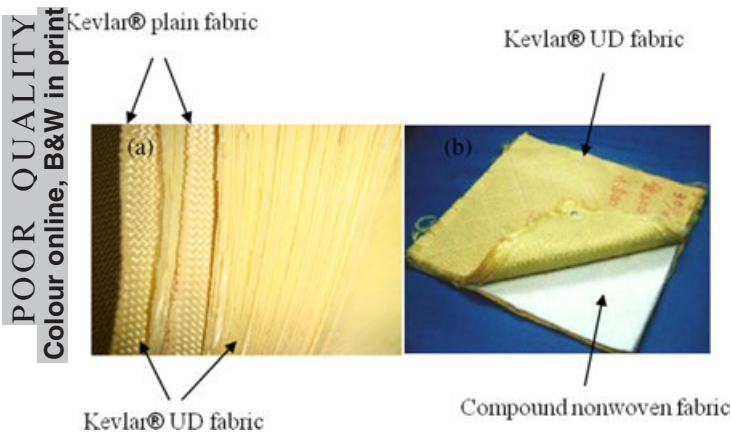


FIG. 3—Pictures of (a) commercial exemplar vest and (b) new armor target.

layers of Kevlar® plain fabrics and two layers of Kevlar® UD fabrics. The outer part of the vest was made from 44-ply Kevlar® UD fabrics, so that all projectiles that hit the vest encountered fifty layers of fabric in total, with 44 layers in the outer vest and six layers in the cushion (shown in Fig. 3).

**Dropping Weight Impact Test**

We used a dropping impact test to simulate a bullet-resistant vest made with our new armor being struck by a bullet. The dropping impact test was conducted according to ASTM D2794 (Standard Test Method for Resistance of Organic Coatings to the Effects of Rapid Deformation: Impact). We used the 10 cm by 10 cm specimens of our new nonwoven material and measured the kinetic energy by a dropping impact test instrument (custom made for this purpose by Kuang Ming, Taiwan), shown in Fig. 4. The dropping height was 0.5 m, and the weight of the dropping head was 9.04 kg. The impact head, shown in Fig. 5, was shaped to simulate a 9-mm bullet. The test was performed once for each 10 cm by 10 cm piece of material, and there were ten measurements for each filament area density.

**Ballistic Impact Tests**

We used a 9-mm Beretta 92FS handgun loaded with full metal jacket ammunition for the bullet-shooting test. The ballistic test was carried out at room temperature for both the new material and the exemplar commercial vest. We aimed at the center of the target



FIG. 4—Dropping weight impact test equipment.



FIG. 5—Dropping weight impact head shown with 9-mm bullet.

while shooting. The photoelectric light screen was a solid-state ballistic screen (MV Ordnance Industries, USA, model number 6100), and the chronograph was a velocity-computing chronograph (MV Ordnance Industries, USA, model 4010P). Each piece of new armor was a 30 cm by 30 cm slab, and the exemplar commercial vest target was a conventional vest. Each target was installed in a case that measured  $400 \times 400 \times 140 \pm 2$  mm, and special clips held each piece of armor in place against a clay witness. Each clay witness allowed measurement of the depth of indentation from ballistic impact. The impact velocity was adjusted to be around  $367 \pm 15$  m/sec according to the standard NIJ 0101.04 level that refers to armor intended to stop pistol rounds in calibers such as 9-mm and 0.357 Magnum. Figure 6 displays the setup for the shooting test based on NIJ 0101.04 level. Each projectile was a full metal jacket bullet whose mass was 7.8 g and whose diameter was 9 mm. Each target was shot four times. Ten samples from each variant of the new material were tested. The measurements were averaged.

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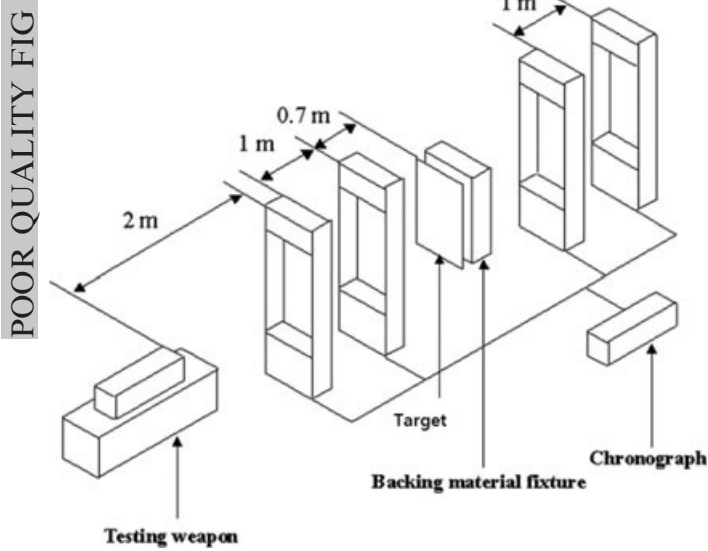


FIG. 6—The setup for the shooting test.

**Results and Discussion**

*Influence of Density of Vectran Filaments Per Unit Area on the Maximum Impact Load of the Compound Nonwoven Fabric*

Figure 7 shows that our compound nonwoven fabrics with more Vectran filaments were able to bear greater maximum impact loads, and it means the compound nonwoven fabrics was strong enough to bear the force that is exerted against the chest of the wearer. The filaments absorbed and dispersed energy, and filament area density was directly proportional to the indentation depth of the supporting clay witness. All five types of our new armor showed impact resistance and stress dispersion that were directly proportional to the area density of Vectran filaments. Further, filament area density was directly proportional to propagated-fracture energy and inversely proportional to initial-fracture energy.

*Influence of Density of Vectran Filaments Per Unit Area on the Kinetic Energy of the Compound Nonwoven Fabric*

A bullet-resistant vest must provide its wearers with impact resistance and a cushioning effect. Past research has shown that stainless steel screen mesh and chloroprene rubber can provide a better

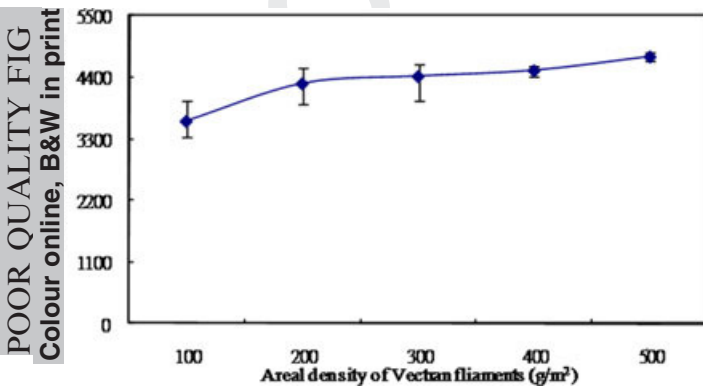


FIG. 7—Maximum impact load of compound nonwoven fabrics with various filament densities per unit area.

cushion effect but worse impact resistance than a filament laminate (18). The dropping impact test provided data concerning low-velocity impacts on our materials. Table 1 shows the kinetic energy levels of the five varieties of our new nonwoven fabric. The ratio of propagated-fracture energy increased with the increment of area density of Vectran filaments within the compound nonwoven fabric; therefore, area density of filaments was proportional to dissipation of kinetic energy.

*Results of the Ballistic Impact Test*

The ballistic impact tests subjected samples of armor to high-velocity impacts; in these tests, the Kevlar® UD fabrics stopped and blunted the projectile. The purpose of our new nonwoven armor is to prevent nonpenetration trauma, and its effectiveness at that task can be inferred from the indentations left in the clay witnesses.

Table 2 shows the results of the ballistic impact tests. The new armors showed ballistic impact resistance directly proportional to Vectran filament area density. In particular, the V400 + 28UD variant of the new material showed results comparable with the commercial exemplar, and the V500 + 28UD showed the best results of the present study. The indentations of V500 + 28UD were about 92% as deep as the indentations of 44UD + 6-Ply Kevlar® (commercial exemplar vest), that is to say, the new armor showed an 8% improvement in ballistic protection compared with the commercial exemplar vest. The compound nonwoven fabric enlarged the impact areas, dispersed the energy, and cushioned ballistic impacts. This shows that the new armor would be very effective in reducing nonpenetration trauma because of ballistic impact. The compound nonwoven fabric also reduced the number of layers required for the bulletproof vest, and vests produced with the new armor would have lower manufacturing costs than commercial exemplar vest. Moreover, vests produced with our new armor would weigh 77.5% as much conventional 44UD + 6-Ply Kevlar® vests (commercial exemplar vest), that is to say, our new armor is 22.5% lighter than conventional armor.

TABLE 1—Kinetic energy of the compound nonwoven fabric compared with area density of Vectran filaments.

Area Density of Vectran Filament (g/m <sup>2</sup> )	The Ratio of the Initial-Fracture Energy and the Total Energy (%)	The Ratio of the Propagated-Fracture Energy and the Total Energy (%)
100	67.8	32.2
200	67.5	32.5
300	62.5	37.5
400	62.2	37.8
500	61.2	38.8

TABLE 2—Comparison of the ballistic impact test between new armor and commercial exemplar vest.

Target Description	Impact Velocity (m/sec)	Indentation Depth (mm)
V100 + 28UD	352	23.6
V200 + 28UD	349	23.6
V300 + 28UD	357	21.6
V400 + 28UD	353	19.3
V500 + 28UD	348	18.1
44UD + 6-Ply Kevlar®	355	19.6

44UD + 6-ply Kevlar® stood for the commercial exemplar vest.

Table 3 shows the area density of the Vectran filaments and the thickness for each variety of armor. While the new armors were all thicker than the commercial exemplar vest, they were lighter in weight, had fewer layers, and cost less money to manufacture than the commercial exemplar vest.

#### Mechanism of Energy Absorption of the Compound Nonwoven Fabric

Various physical phenomena, including fiber breakage, matrix failure, delaminations, elastic waves, friction, and so on, can

TABLE 3—Comparison of ballistic impact test based on the area density of Vectran filaments and the thickness of armor between new armor and commercial exemplar vest.

Target Description	Area Density (g/m <sup>2</sup> )	Thickness (mm)
V100 + 28UD	4318	6.81
V200 + 28UD	4405	6.98
V300 + 28UD	4511	7.19
V400 + 28UD	4603	7.38
V500 + 28UD	4747	7.71
44UD + 6-Ply Kevlar®	5940	6.53

44UD + 6-ply Kevlar® stood for the commercial exemplar vest.

dissipate the energy of a projectile impact. Figure 8 shows cross-sections of our nonwoven material before and after projectile impact. The Vectran filaments dissipated some energy, but the fibers that had been bonded by needle punching also broke apart. Impacts caused indentations and deformations around the impact areas, and the Vectran filaments slid and were constrained by the limits set by the needle-punched bonds. In some cases, the kinetic energy broke the needle-punched bonds. The compound nonwoven fabric structure resists compression and impact to the extent that the bonds remain intact.

An impact at high velocity creates a large impact area and engages a large number of fibers and filaments. Within the impact area, the bonds perpendicular to the fabric surface are destroyed by sliding filaments. The destruction of the compound nonwoven fabric shown in Fig. 8(a,b) explains how the compound nonwoven fabric cushioned the ballistic impact.

#### Conclusion

The results of the dropping weight impact test showed that each type of new armor had ballistic impact resistance and cushioning corresponding to its area density of Vectran filaments. Our new armor type with 400 g/m<sup>2</sup> of Vectran filaments showed ballistic impact resistance comparable with that of a commercial exemplar vest made of 44-ply Kevlar® UD fabrics with a 6-ply Kevlar® cushion. That compound nonwoven fabric cushion could be considered equivalent to 16-ply Kevlar® UD fabrics. Compared with conventional armor, our new armor reduced indentation depth by 8%, and also reduced the weight of the armor by 22.5%.

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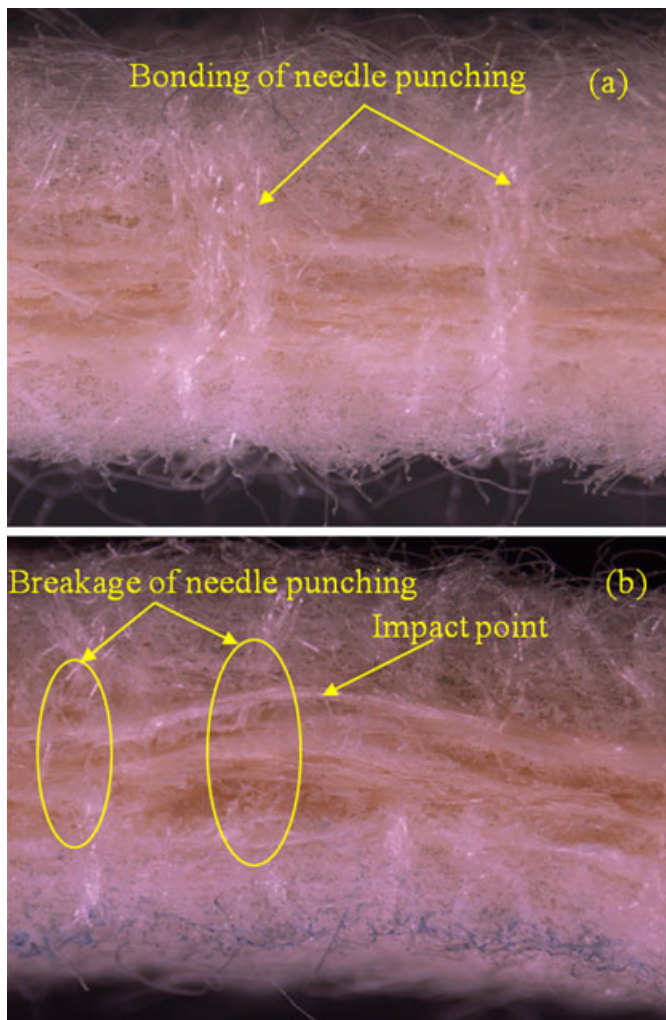


FIG. 8—Cross-section of compound nonwoven fabric (a) before and (b) after impact.

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