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Design and development of three-dimensional woven fabrics with stab resistance

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Abstract. In this paper, the body protective composite, shaped like an armor, is fabricated via three-dimensional manufacturing and hot processing. By one shot process, a 'sandwich structure' is formed. It is constructed with multi-layer woven fabrics and various fibres.The upper layer and the lower layer are formed with high-strength aramid fibres, whilst the middle layers are constituted by polypropylene (PP) fibres.Due to the high melting point of armaid fibres, when PP fibres are heated to melt, armaid fibres still exist in the form of yarns. The yarns connect each melt PP blocks, and overall forms folding and wearable anti-damage fabrics. Through finishing process, these fabrics could be made into suits of armor, which can be applied in the fields of protective garments for policemen and soldiers

Keywords: Stab-resistant Fabrics, Sandwich Structure, Fabric Design, Weaving, Hot-melt Compound

1. Introduction

In the early-stage, the stab resistant fabrics were mainly made of hard materials, such as animal skins, metals and ceramics. Those fabrics typically appeared in the form of armors in the ancient China. However, due to the heavy weight, they normally limited the flexibility of human bodies. Nowadays, the stab resistant materials have been developed towards semi-rigid, soft and liquid materials. Many researchers have reported the recent design and development of the stab resistant fabrics. Zhao et al. introduced soft metal wires and high performance fibres to weave or knit stab resistant fabrics [1]. High density fabrics had been weaved, non-woven and compounded by high performance fibres in order to promote their stab resistant properties [2]. Shear Thickening Fluid (STF) was also employed to weave liquid protective clothing [3, 4]. Despite of its good stab resistance, this kind of material is very expensive. To promote the stab resistant property, composites compounded with resin and fabrics have been becoming a new trend[5], which can be achieved through coating, dipping and laminating. For example, aramid no-woven cloth and aramid woven cloth (sandwich structure composite) have been laminated via traditional compound technique with various adhesives [6]; aramid fabrics, dipped in thermoplastic resin, yet possess poor permeability and comfort [7]; by screen printing and UV curing methods, stab resistant materials can also be formed, with resin regularly arranged on the base cloth [8]; fabrics have been successfully coated with resin via net plate performing process, with resin divided evenly [9]; some resin films have been bonded directly to garment fabrics [10]

2. The design mechanism of the overall structure

By adopting multi-layer woven cloths and various fibres, the stab-resistant fabric is achieved. Figure 1 and Figure 2 show its morphology structure and profile structure after hot processing. The 'armour' block, shown in Figure. 1, possesses sandwich structure. Each block is connected by multi-layer cloths, constructed with high density, high strength and high melting point fibres. Figure 2 shows that, in the block region, the upper layer and the lower layer are formed with high density cloths, whilst the middle layer is constructed by multi-layered cloths made of low melting point fibres. Whenthe middle layer is heated to melt, the upper layer and lower layer still exist in the form of yarns. The yarns connect each melt block in the middle layer, and overall forms a folding and wearable stab resistant fabric.

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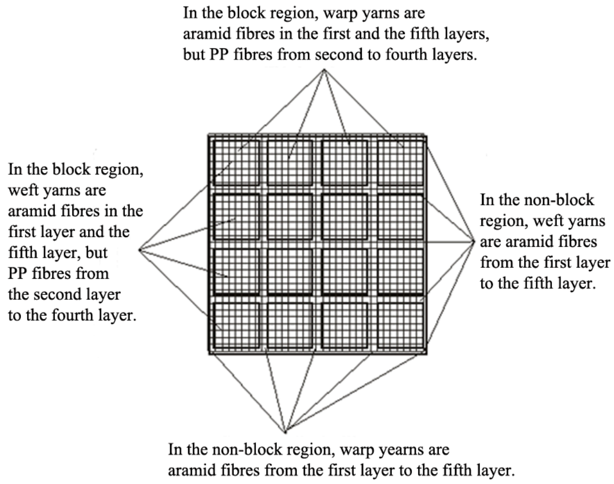

Fig. 1: Morphology structure of the three-dimensional anti-stab fabrics

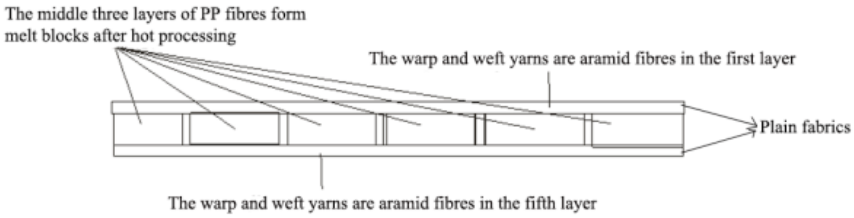

Fig. 2 The profile structure after hot processing

3. Fabric design

3.1 Materials

High strength filaments are required for the upper and lower layers. The middle layer needs to choose some materials which melting point are relatively lower than those of the upper and lower layers. In this paper, aramid fibres and polypropylene (PP) fibres were chosen and used as received. The melting point of aramid fibres is about 560 °C, while that of PP fibres is 168 ~ 174 °C with thermal decomposition temperature of 350 ~ 380 °C. The difference in melting point, could ensure when PP fibres melt, aramid fibres still exist in the form of yarns to form fabrics.

3.2 Methods

3.2.1 Fabric design

(1) Design of the upper layer and the lower layer: plain weave is employed in the block regions and non-block regions.

(2) Design of the middle layer: a. In the block region: any pattern can be taken in this area, such as plain weave and twill weave. It also works with only warp threads. b. In the non-block region (joint area): correspondingly, weft yarns can only be hired in this area; plain weave and twill weave can also be applied. It is noteworthy that, the joint area needs to be kept away when hot processing.

(3) Connectivity between layers: in the block region, layers are melt into one integrated mass, whilst the joint area need remain its natural state and tie together in order to promote the integrity and the stab resistance. In this paper, two kinds of connectivities are carried out:

Case 1: warp float threads are applied in the block region; the upper layer and the lower layer are interweaved together in the joint area.

Case 2: in the block region, three layers of plain weave cloth are served as the middle layer; in the joint area, three layers of 2/1 twill weave cloth in the middle layer are interweaved together.

3.2.2 Determination of the looming draft

In the weave pattern, ■ is the warp float point in the upper layer; ⊠ is the warp float point in the lower layer; ◆ is the warp float point in the first layer of the middle; ● is the warp float point in the second layer of the middle; ▲ is the warp float point in the third layer of the middle; ☆ is the interweaved point; ○ is the the lifers.

As shown in Figure 3 (Case 1). The yarn A and B are the polypropylene (PP) fibres, which are formed blocks after hot melting. The arrangement in warp is 1:2, the upper warp is 1 yarns, the middle layers warp is 2 yarns. Figure 4 ~ 7 show the weave and the draft of Case 2: A indicates the block region (Figure 4) ; B shows the joint area (Figure 5) ; Figure 6 is weave pattern of case 2 ,which include different parts; Figure 7 shows the draft. Five warp threads drawing through per reed dent.

As shown in Figure 4 and Figure 6, NJ1 and NW1 mean the numbers of warp repeat and weft repeat in the block region, while NJ2 and NW2 indicate the number of warp repeat and weft repeat in the non-block region, respectively. These four parameters vary according to the fabric density and the size of block regions as well as non-block regions.

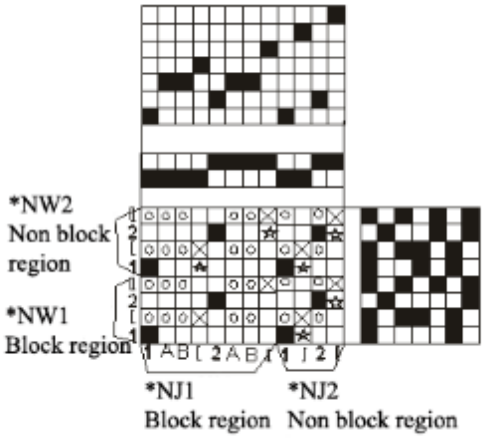

Fig.3 Weaving plan of case 1

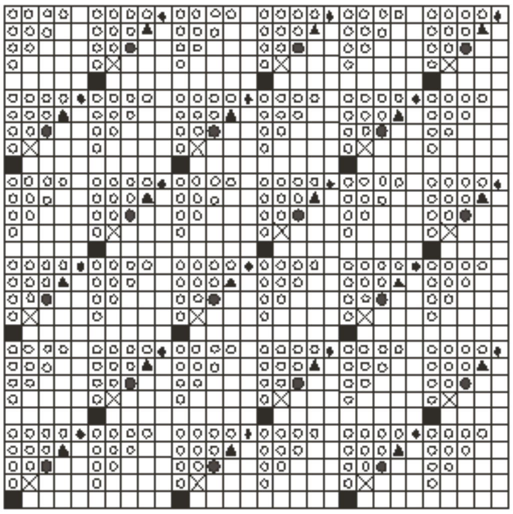

Fig.4 The block region of Case 2

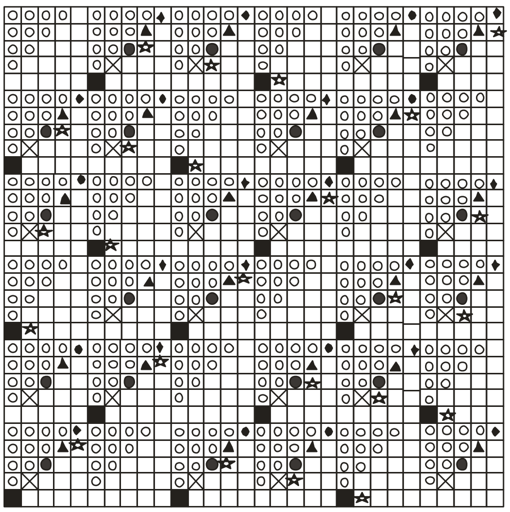

Fig.5 The non-block region of Case 2

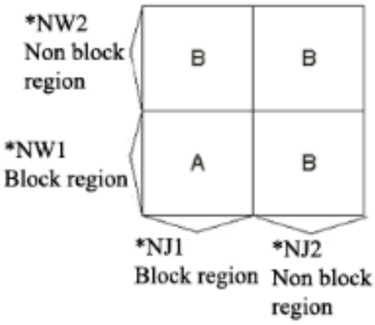

Fig.6 The weave pattern of case 2

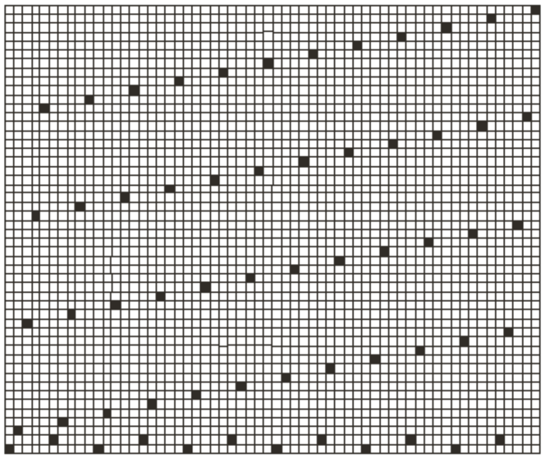

Fig.7 The draft of case 2

3.2.3 Determination of the fabric density and the number of threads in the yarns

The fabric densities of the upper layer and the lower layer play significant roles in the stab resistance property of this composite; meanwhile the achievement of weave is also affected by this. Experimental results show that the optimal effect appears when thread densities of warp and weft yarn are both 120/10cm.

Table 1 and Table 2 show the number of yarns in Case 1 and Case 2, respectively (on the condition that every block region is 15 mm × 15 mm, and the joint length between two blocks is 5 mm). Figure 8 demonstrates the sample before weaving but after thermal compounding.

Table 1 The number of yarns in the block regions and non-block regions of Case 1

Items	Block region			Non-block region	
	The upper layer	The middle layer	The lower layer	The upper layer	The lower layer
Nw1	9	0	9	9	9
Nw2	3	0	3	3	3
Nj1	9	9	9	null	null
Nj2	null	null	null	3	3
Number of warp yarns	18	36	18	6	6
Number of weft yarns	24	0	24	24	24

Table 2 The number of yarns in the block regions and non-block regions of Case 2

Items	Block region					Non-block region				
	The upper layer	the middle layer			The lower layer	The upper layer	The middle layer			The lower layer
		1st	2nd	3rd			1st	2nd	3rd	
Nw1	9	9	9	9	9	9	9	9	9	9
Nw2	3	3	3	3	3	3	3	3	3	3
Nj1	9	9	9	9	9	null				
Nj2	null					3	3	3	3	3
Number of warp yarns	18	18	18	18	18	6	6	6	6	6
Number of weft yarns	24	24	24	24	24	24	24	24	24	24

Fig.8 The sample picture after weaving but before thermal bonding

4. Methods of the hot processing

During the hot processing, the block region is heated to melt, but the non-block region is avoided in order to maintain the pliability of the composite. Figure 9 shows the ceramic-strip hot plate, which is applied for the thermal compound of Case 1. When heated, the ceramic hot plate clamps the blocks and slides in the direction of weft yarns, so that the non-block region is kept away in case of damage. Figure 10 shows the stainless-block hot plate, which is served as the heater for the sample of Case 2. Its clamping direction is available in warp and weft directions.

Fig.9 The ceramic strip hot plate

Fig.10 The stainless block hot plate

At present, hot plate is currently in use in laboratory. When heated, the clamping force of the hot plate should be moderate. For factory production, roller heating is more suitable. It is noted that, the distribution of heating area has to be consistent in each block of the stab resistant fabric.

Temperature control is extremely vital to thermal compound. Higher temperature will damage the upper layer and the fibres in the joint area. Lower temperature cannot ensure the blocks melt.

5. Research prospects

For the time being, the optimum design parameters still need to be determined with further experimental data. Several aspects for future study are provided in the following sections.

(1) The size and the thickness of the blocks: the stab resistant effect and the comfort of the fabric are affected by this. Further experiments will be carried out to find the basis justification.

(2) The size of the joint area: it will affect the softness and the stab resistant effect. The best combination of the two needs further progress.

(3) Materials selection: theoretically, many materials can be applied. For example, aramid and high strength polyethylene (HSPE) fibres for upper and lower layers; polypropylene (PP) and Nylon fibres for the middle layer.

(4) The state of the blocks in the middle layer: in this paper, the three middle layers are plain weave and interweaved together. However, it is still unknown whether direct feeding of the middle layer without interweaving will attain better stab resistant effect or not. This needs to be studied further.

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