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Evaluation of Stab Resistance of Coated UHMWPE Fabric

DOI: 10.5604/01.3001.0013.7319

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Abstract

In recent years, individual protection has attracted much attention in the area of personal safety, especially stab resistant clothing. Nowadays, fabrics of high performance fibre are often used in stab-resistant clothing. Therefore, in this paper ultra-high molecular weight polyethylene(UHMWPE) fibre fabrics were used to explore their distribution of boron carbide(B_4C) particles. The effect of different processing techniques on stab resistance was discussed. Finally, it was found that when the particle dimension was 5 microns, the coating thickness 100 microns, the coating temperature 64 °C and the particle and binder ratio 2:3, the stab-resistance performance of the fabrics was best. The stab resistance of multi-layer fabrics was also discussed, and it was found that the relationship between energy absorbed and the number of layers was changed by hard particles.

Key words: *stab resistant, fabrics hard particles, coating.*

Introduction

With the development of high-performance fibres, the number of body armours with stab protection has increased [1]. There are ultra-high molecular weight polyethylene fibre (UHMWPE), aramid fibre, poly (p – phenylene benzobisoxazole) (PBO) fibre, ceramic fibre, carbon fibre, and so on [2-4]. Because UHMWPE fibres are soft and lightweight, stab resistant fabric has been mostly made of UHMWPE fibres [4] and widely used in stab resistant clothing.

There are some researches about stab resistance. Some used resin to enhance the stab resistance property [5-6]. ZW Gu made stab-resistant body armour by alternating the non-woven layer and plain weave fabric layer [7]. Shear thickening fluid (STF) was also used to prevent stabbing [8-12]. YM Zhao used fabrics with hard particles to make stab-resistant materials [13]. There have been many kinds of hard particles used in stab-resistant materials, such as silicon carbide (SiC), cubic boron nitride (CBN), boron carbide (B_4C), aluminium oxide (Al_2O_3), crome metal (Cr) etc [13].

In this paper, woven fabric of UHMWPE was used as a stab resistant fabric. Considering the density, hardness and practical application, B_4C was herein chosen for the following stab resistance experiment.

Experimental

Materials

B_4C particles were purchased from Mudanjiang Boron Carbide Factory. The particle dimension was 2.5, 5, 10 and 20.5 μm. The woven fabrics were made of UHMWPE. The weight per square metre of the fabrics used in this paper was 180 g/m^2.

Preparation of fabrics with hard particles
The coating liquid was stirred for 30 min by a magnetic stirrer at room temperature, which was then transferred onto the fabrics. The coated fabrics were baked for 10 min in an oven of 80 °C, and then baked for 5 min at 110 °C. Finally, the fabrics were removed from the oven.

Experimental equipment

The stab-resistance property was tested by a quasi-static puncture instrument, shown in ***Figure 1***. During the test, the

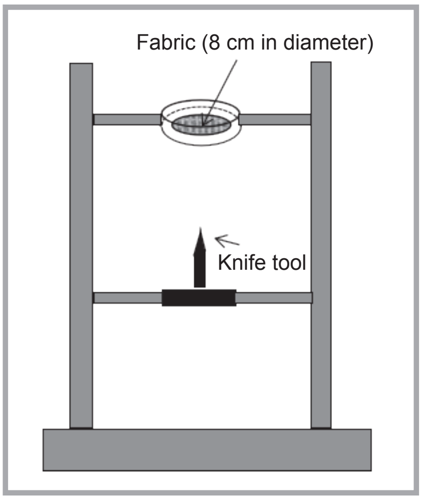

Figure 1. *Quasi-static puncture instrument.*

Table 1. *Porosity of particle structure [14].*

Stack form	Porosity, %	Volume utilization ratio, %
Simple cube structure	$\frac{\frac{4}{3}\pi r^3}{a^3}$ = 47.64	52.36
Body-centered cubic structure (BCC)	$\frac{2\times\frac{4}{3}\pi r^3}{\left(\frac{4}{\sqrt{3}}r\right)^3}$ = 31.98	68.02
Face-centered cubic packing (FCC)	$\frac{4\times\frac{4}{3}\pi r^3}{\left(2\sqrt{2}r\right)^3}$ = 25.95	74.05
Hexagonal closest packing (HCP)	$\frac{2\times\frac{4}{3}\pi r^3}{11.3138r^3}$ = 25.95	74.05

knife went up and touched the sample fabric. The instrument can record data of the maximum load and energy absorbed.

Results and discussion

Theory calculation of hard particles' structure

Particle distribution on the fabric affected the final physical property. There are four arrangements, such as a simple cube structure, body-centered cubic structure, face-centered cubic packing and hexagonal closest packing, as illustrated in ***Figure 2***.

From ***Figure 2***, it can be seen that the particles occupied some spaces, and that there are void spaces. In order to analyse the specific distribution, the volume utilisation and porosity ratio of four forms were calculated as in ***Table 1***.

The porosity of several packing structures is shown in ***Table 1***. The volume utilisation ratio of particles was independent of the radius of the particles, and it was constant under the same structure mode and thickness. It can be observed that FCC and HCP were the closest packing, and that the volume utilisation ratio was the same – 74.05%. It had a guiding effect in preventing stabbing, and hence particles were arranged in these forms as much as possible.

In actual usage, the force would pass down through F_1. Hard particles effectively dispersed the force F, and damage to the bottom fabric was reduced. In order to facilitate analysis of the force, an accumulation structure of particles was assumed in the body-centered cubic structure (BCC). Force analysis of the stab-resistant fabric is shown in ***Figure 3***.

When particles were under pressure F in ***Figure 3.a***, the stressed area of the bottom layer increased with an increase in the thickness of the particle stack h. Thus, the increase in h was conducive to an increase in the bearing capacity of the fabric. The dimension of the particle in ***Figure 3.b*** was smaller than that of the one shown in ***Figure 3.a***; but the area under stress was invariant. The contact point between the particle and fabric increased, thus the distribution of the force on the fabric was more uniform. Therefore, it was considered that the small particle dimension was better for stab resistance under the same conditions.

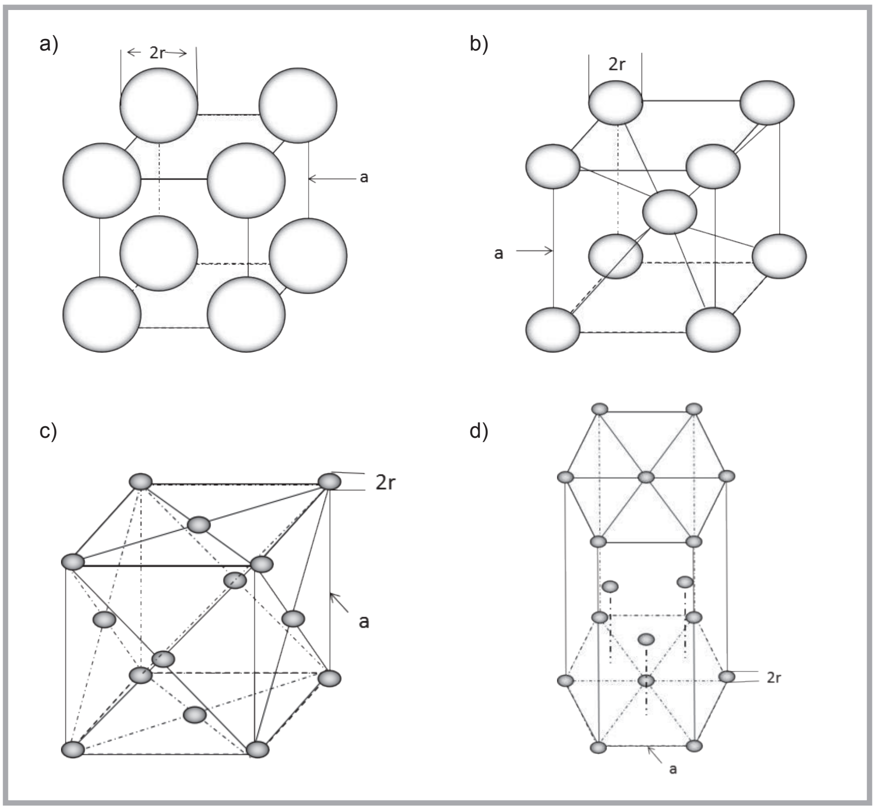

Figure 2. *Structure of particles: a) simple cube structure, b) body-centered cubic structure, c) face-centered cubic packing, d) hexagonal closest packing.*

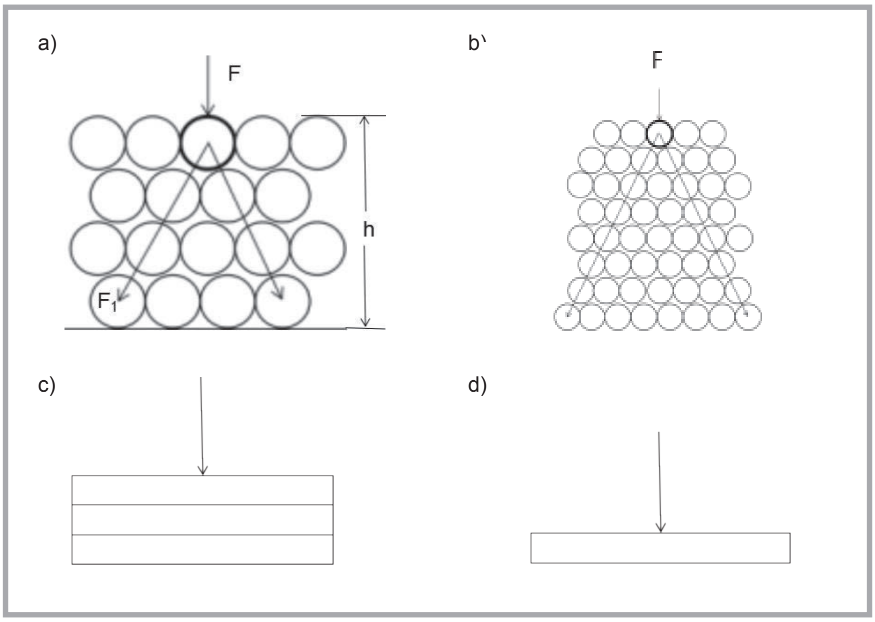

Figure 3. *Fabric stress diagram: a) coated fabric, b) small size of particles, c) three layers of original fabrics, d) one layers of original fabrics.*

When the particles were not on the surface of the fabric, the force was transmitted vertically downward. It was assumed that only the forces in the vertical direction were considered. If one layer of the original fabric, shown in ***Figure 3.d***, was stabbed under force F, then the three layers of the original fabric, shown in ***Figure 3.c***, were cut under a force three times more than F. If one layer of the fabric with hard particles was stabbed under force F, then three layers of the coated fabrics were stabbed under a force about nine times more than F. It was assumed that the energy absorbed by the fabrics was *W* in ***Equation (1)***, the displacement

Table 2. *Effect on stab resistance of different dimensions of particles.*

Dimension, μm	Thickness, μm	Energy absorbed, J	Maximum load, N
2.5	100	0.6683	22.53
5	100	0.7277	24.39
10	100	0.6555	23.06
20.5	100	0.6471	20.78

Table 3. *Effect on stab resistance of different numbers of layers.*

Thickness, μm	Dimension, μm	Temperature, °C	Ratio of particle and binder	Maximum load, N	Energy absorbed, J
50	5	29	1:2	28.84	0.8478
75	5	29	1:2	27.15	0.8425
100	5	29	1:2	30.72	0.9355

Table 4. *Effect on stab resistance of different temperatures of the coating liquid.*

Coating liquid temperature, °C	Dimension, μm	Thickness, μm	Ratio of particle and binder	Maximum load, N	Energy absorbed, J
29	5	100	1:2	30.72	0.9355
53	5	100	1:2	32.77	0.9501
64	5	100	1:2	35.28	0.9885

Table 5. *Effect on stab resistance of different ratios of B4C powder and binder.*

Ratio of particle and binder	Dimension, μm	Thickness, μm	Temperature, °C	Maximum load, N	Energy absorbed, J
1:6	5	100	64	29.20	0.8980
1:3	5	100	64	30.67	0.9036
1:2	5	100	64	35.28	0.9885
2:3	5	100	64	35.77	1.0615

of the knife during stabbing – s, and the force – F.

$$W = F*s \tag{1}$$

The thickness of the fabric was very small compared with the displacement of the knife, and hence it can be ignored. Thus, the energy absorbed by the three layers of the original fabrics was about three times that by the one-layer fabric, and that by three layers of coated fabrics was about nine times higher. The relationship between energy absorbed and the number of layers was changed by hard particles.

Effect on stab resistance of different particle dimensions

The particle dimension will have a influence on stab resistance. In this paper, different particle dimensions were analysed, the results of which are shown in ***Table 2***.

Here, four dimensions (2.5, 5, 10, 20.5 μm) were discussed. It can be observed that during cutting, the energy absorbed increased from 0.6683 to 0.7277 J but then decreased from 0.7277 to 0.6471 J. The maximum load rose from 22.53 to 24.39 N but then decreased to 20.78 N. Firstly, the energy absorbed increased with a decrease in the particle dimension but then decreased, which was not exactly the same as in the previous analysis, probably due to the fact that the horizontal force could not be completely ignored. When the particle dimension was 5 μm, the energy absorbed and maximum load were largest. Hence, 5 micron particles were used for the following experiments.

Effect on stab resistance of different numbers of layers

In order to establish the effect of the number of layers on stab prevention, different numbers of layers were explored. The results are displayed in ***Table 3***. Maximum load meant the maximum force that the fabric could withstand during stabbing.

The thickness was adjusted from 50 to 100 μm. When increasing from 50 to 100 μm, the maximum load rose from 28.84 N to 30.72 N, and the energy absorbed from 0.8478 to 0.9355 J, showing that the stab resistance became larger when the thickness increased. Therefore, 100 μm thickness was chosen to prevent stabbing.

Effect of stab resistance under different coating temperatures

The coating temperature affected stab resistance performance. Therefore, different temperatures were analysed, data of which are displayed in ***Table 4***.

It was shown that when the temperature increased, the energy absorbed increased from 0.9355 to 0.9885 J and maximum load from 30.72 to 35.28 N, which proved that an increase in temperature was conducive to an improvement in the stab resistance property. The adhesive stuck out when the temperature was too high, hence the highest temperature was 64 °C in this experiment, at which the energy absorbed was highest. Thus, 64 °C was chosen as the coating liquid temperature.

Effect on stab resistance of different ratios of B_4C powder and binder

The effect of stab resistance is influenced by the ratio of B_4C powder and binder. Thus, different ratios of B_4C powder and binder were researched, the results of which are shown in ***Table 5***.

Table 5 shows that during the stabbing, the maximum load rose from 29.20 to 35.77 N and the energy absorbed from 0.898 to 1.0615 J. The increase in particle density in the binder was conducive to an increase in stab-resistance performance. It contributed to the arrangement of particles in forms of FCC and HCP. When the ratio of particles and binders was 2:3, the energy absorbed and the maximum load of the coating fabrics were largest.

Effect on stab resistance of different numbers of fabric layers

In order to explore the relationship between stab resistance and the number of fabric layers, different numbers of fabric layers were analysed. Here, the original fabrics and fabrics coated with epoxy resin and hard particles were used.

It was found that the energy absorbed by the three layers of the original fabrics was about 2.7 times that by one layer, shown in ***Figure 4***, while with three layers of the coated fabrics it was 4.3 times, shown in ***Figure 5***. The increase in energy absorption of the coated fabrics was not the same as in the theoretical assumption. However, the relationship between the energy absorbed and the number of layers was changed. The coating method was conducive to an increase in energy

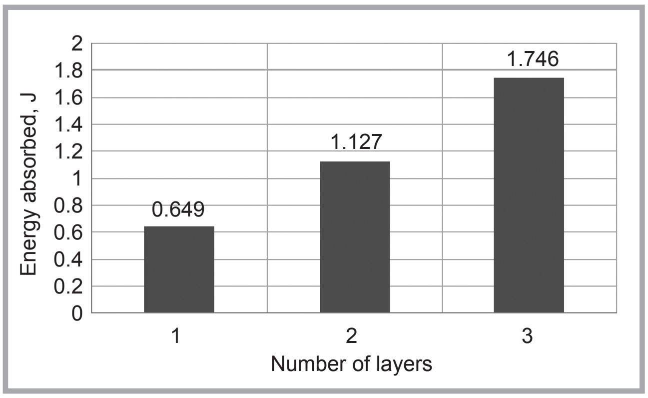

Figure 4. *Effect on stab resistance of different numbers of layers of the original fabric.*

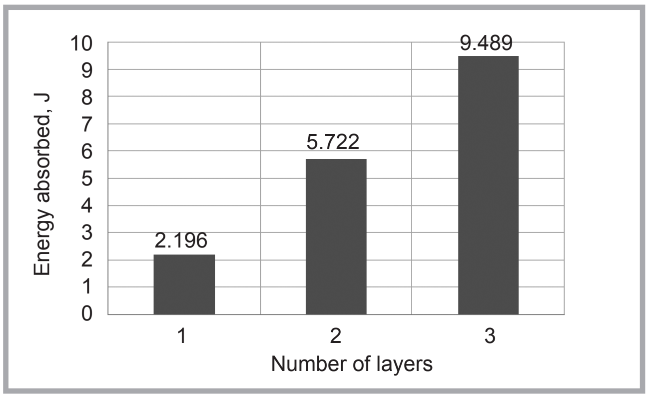

Figure 5. *Effect on stab resistance of different numbers of layers of the coated fabric.*

absorption with an increase in the number of layers of the fabric.

It showed the stab resistance property of the original fabric, displayed in ***Figure 4***. By comparing the coated fabric in ***Figure 5*** with the original fabric, it can be observed that the energy absorbed by the coated fabric was 3.38 times that by the original fabric. The energy absorbed by the fabric coated with polyacrylic, shown in ***Table 5***, was 1.64 times that by the original fabric. The coated fabric had better stab-resistance performance. The coated fabric made of epoxy resin was hard, thus polyacrylic is more suitable for soft coated fabrics.

Conclusions

UHMWPE fibres play an important role in stab resistance. In this paper, UHMWPE fabric with hard particles was used to prevent stabbing. The stab resistance property was influenced by the distribution of particle conformation. The volume utilisation of four forms were analysed in this paper, and tt was found that the volume utilisation of particles was independent of the radius of the particles. The effect on stab resistance of different numbers of fabric layers was analysed. It was considered that the coating was beneficial to energy absorption.

At the same time, several kinds of particle dimension (2.5, 5, 10, 20.5 μm) were discussed. When the particle dimension was 5 microns, the stab-resistance performance of fabrics with hard particles was best. Then, the coating thickness was ranged from 50 to 100 μm. A 100 μm coating thickness had a better stab resistant effect than 50 and 75 μm. When the temperature (29, 53, 64 °C) of the coating liquid was increased, the maximum load and energy absorbed of the fabrics also increased. When the coating liquid temperature reached 64 °C, the stab resistance performance was best. Finally, the effect on stab resistance of different ratios of the particle to binder was compared. When the ratio of the particle to binder reached 2:3, the energy absorbed by the fabrics was highest. A series of experiments showed that the stab-resistance performance of the coated fabric was best when the particle dimension was 5 microns, the coating thickness 100 microns, and the coating temperature 64 °C, at a ratio of the particle to binder of 2:3. And it was found that the coating with hard particles was conducive to an increase in the energy absorbed with an increase in the number of layers of the fabric.

In this paper, the energy absorbed byfabric in the best arrangement was 1.64 times that by the original fabric. The results showed that fabrics with hard particles provided good resistance against stab threats. It can be a good reference for individual protection.

Acknowledgements

This work was supported by the National Key R&D Program of China 2016YFC0802802.

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Received 03.01.2018 Reviewed 12.07.2018