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RESEARCH ARTICLE

Cut-resistant performance of Kevlar and UHMWPE covered yarn fabrics with different structures

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ABSTRACT

Kevlar fiber and UHMWPE fiber are widely used in stab-resistant materials at home and abroad. Researches focus on the selection of a single fiber as raw material, but rarely combine the two high-performance fibers for the fabrication of stab-resistant fabrics. Kevlar fiber and UHMWPE fiber were utilized to prepare twelve kinds of covered yarns with different structures in this paper. Tensile performance of the covered yarns and cut-resistant performance of the covered yarn fabrics were tested, respectively. The results show that tensile performance of the covered yarns is better than pure Kevlar or UHMWPE yarns with same linear density. Tensile performance of the covered yarns decreases with the increase of twists, and the covered yarns show different failure modes with different twists. The cut-resistant performance of covered yarn fabrics are better than that of pure Kevlar or UHMWPE fabrics; and the cut-resistant effect with Kevlar fibers wrapping around the core fibers is superior than that with UHMWPE fibers. The cut-resistant performance of the covered yarn fabrics decreases with the increase of twists of the covered yarns. For the same kind of covered yarn structures, there is a positive correlation between cut-resistant performance of the covered yarn fabrics and tensile strength of the covered yarns. However, no correlation is observed for different covered yarn structures. The results lay a theoretical foundation for the structural optimum of cut-resistant and stab-resistant clothing.

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KEYWORDS
Kevlar fiber; UHMWPE fiber; covered yarn; cut-resistant performance; tensile performance

1. Introduction

In the process of social development, personal protective materials always play a very important role. Whether it is the encounter between soldiers on the battlefield in ancient times or the frequent occurrence of various violent terrorist incidents today, it is inseparable from the protective role of protective materials. In China, the rules always been very strict with the control of guns, but has little control over sharp knives. However, the harm caused by knives should not be underestimated. Therefore, the research of stab-resistant materials has extremely important practical significance and theoretical value (Lin et al., 2008; Tian et al., 2019; Zhang et al., 2012).

Because of their special functionality, stab-resistant materials have high requirements on raw ones of fibers. The fibers must have excellent mechanical properties, such as Kevlar fibers (Tae et al., 2010; Yang, 2010), UHMWPE fibers (Huang, 2010; Kong, 2015), and so on. Kevlar fibers' specific strength is 5–6 times than that of steel, and modulus is 2–3 times than that of steel and glass fibers (Zheng et al., 2005) for their excellent mechanical properties, such as high strength, high modulus, light weight (Zheng et al., 2014), *et al.* Meanwhile, UHMWPE fibers even own better mechanical properties (Barron & Birkinshaw, 2005; Gul et al., 2003; Zhao et al., 2012), with their specific strength 2.6 times than that of carbon fibers, and 1.7 times of aramid fibers (Gu, 2015). Therefore, Kevlar fibers and UHMWPE fibers are widely used in stab-resistant materials and bullet-proof materials domestically and abroadly (Horsfall, 2000; Shin et al., 2003; Tian, 2017). In addition, these researches focus on the selection of a single fiber as raw material, but rarely combine the two high-performance fibers for the fabrication of stab-resistant fabrics.

However, the above two high performance fibers also have some shortcomings. The light and UV resistance of Kevlar fibers are poor. At the same time, Kevlar fibers have better transverse shear properties but worse longitudinal tensile properties. On the contrary, UHMWPE fibers' light resistance is good, and its strength has only slightly decreased when exposed out of outdoors for more than 1 year. But UHMWPE fibers have low melting point, and the maximum service temperature is less than 120 °C (Fan et al., 2016; Tian et al., 2020). More critically, UHMWPE fibers have excellent longitudinal tensile properties, but worse transverse shear properties.

The covered spinning process is a yarn reprocessing technology, which can compound different kinds of yarns to give the composite yarn more excellent performance (Ao et al., 2014; Xue, 2002). Therefore, our work will focus on the preparation and cut-resistant performance of covered yarn fabrics.

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2. Experiment

2.1. Materials

Kevlar fiber (600 D) and UHMWPE fiber (400 D) were supplied by Yantai Tayho Advanced Materials Co., Ltd (Shandong, China) and Jiangsu Jonnyma New Materials Co., Ltd (Jiangsu, China), separately. Polyester filaments (1000 D) were provided by Zhejiang Guxiandao Co., Ltd (Zhejiang, China).

2.2. Preparation and tensile performance of covered yarns

2.2.1. Preparation of covered yarns

Kevlar fiber (600 D) and UHMWPE fiber (400 D) were selected as raw materials, and three different kinds of twists (100, 200, 300 twists/m) were utilized to prepare twelve types of covered yarns on the HKV141 hollow spindle wrapping machine. The structures of the covered yarns were shown in Table 1.

2.2.2. Tensile performance test of covered yarns

Tensile performance of covered yarns was tested in a 5569H INSTRON universal testing machine referring to standard of GB/T 3916-2013. The test environment temperature was 18 °C, while the relative humidity was kept as 62%. The sample clamping distance was 200 mm, with the tensile speed was set as 10 mm/min and 5 tests.

2.3. Preparation and cut-resistant performance of covered yarn fabrics

2.3.1. Preparation of covered yarn fabrics

Covered yarn fabrics using plain weave were prepared on a SGA598 semi-automatic sample loom by using polyester filaments (1000 D) as warp yarns, and K/K, K/P, P/K and P/P covered yarns as weft yarns. (K represents for Kevlar, P stands for UHMWPE.) The structures of the above-mentioned fabrics were listed in Table 2.

2.3.2. Cut-resistant performance test of covered yarn fabrics

Cut-resistant performance of covered yarn fabrics was tested in a TDM-100 cut-resistant tester according to standard of ISO 13997-1999 (Zhou et al., 2014). The fabrics were cut into standard samples along the warp and weft directions. The fabrics were cut 15 times with different loads, such that the cut distances were distributed in the ranges of 5 mm~15mm, 15 mm~30mm and 30 mm~50mm. The varied cut loads and corresponding distances of each experiment were recorded. Based on it, the optimal fitting curve of normalized cut distance and load were drawn. Then the load required for the cut distance of 20 mm could be determined according to this curve. The schematic diagram of the cutting test is shown in Figure 1.

Table 1. Structures of twelve kinds of covered yarns.

Twists / Twist direction	Wrapping fiber	Core fiber	Linear density /D
100/S	Kevlar	Kevlar	1200
	Kevlar	UHMWPE	1000
	UHMWPE	Kevlar	1000
	UHMWPE	UHMWPE	800
200/S	Kevlar	Kevlar	1200
	Kevlar	UHMWPE	1000
	UHMWPE	Kevlar	1000
	UHMWPE	UHMWPE	800
300/S	Kevlar	Kevlar	1200
	Kevlar	UHMWPE	1000
	UHMWPE	Kevlar	1000
	UHMWPE	UHMWPE	800

Table 2. Structures of twelve kinds of covered yarn fabrics.

Covered yarn (Wrapping fiber / Core fiber)	Twists / Twist direction	Warp density / ends 10cm-1	Weft density / ends 10cm-1
K/K	100/S	110	160
	200/S	110	160
	300/S	110	160
K/P	100/S	110	160
	200/S	110	160
	300/S	110	160
P/K	100/S	110	160
	200/S	110	160
	300/S	110	160
P/P	100/S	110	140
	200/S	110	140
	300/S	110	140

3. Results and discussion

3.1. Tensile performance of covered yarns

Tensile performance of the twelve kinds of covered yarns, pure Kevlar yarns and UHMWPE yarns were shown in Figures 2 and 3.

Figure 2a shows that tensile performance of four different kinds of covered yarns all decreased with the increased twists, which is due to the wrapping fiber to core fiber contribution function. The spirally wrapping fiber wrapped on the core fiber can contribute its tensile component force along the longitudinal direction of the covered yarns (Huang & Wang, 2017; Xie et al., 1986), which can improve tensile property of the covered yarns. However, tensile component force of the wrapping fiber would reduce gradually with the increased twists of the wrapping yarns, which would cause the strength of the wrapping yarns decreased with the increase of twists.

Among these covered yarns, as shown in Figure 2a, the P/P covered yarn had the largest tensile load when the twist was 100 twists/m; the K/P covered yarn had the largest tensile load when the twist was 200 twists/m; the K/P covered yarn had the largest tensile load when the twist was 300 twists/m. The results showed that the tensile performance of the covered yarns was not only related to the twists, but also related to the selection of wrapping structures.

When the twist was 100 twists/m, the tensile load of K/K covered yarn was 262.7 N, K/P was 256.2 N, P/K was 256.0 N, and P/P was 278.4 N are shown in Figure 2a. Pure Kevlar yarn was 183.6 N, and pure UHMWPE yarn was

210.8 N are shown in Figure 2b. The results showed that the tensile performance of covered yarns was better than pure Kevlar or pure UHMWPE yarns. This is related to the compact effect of the wrapping fiber on the core fiber. The spirally wrapping of the wrapping fiber to the core fiber could form a radial centripetal pressure on the core fiber, which made the structure of core fiber more compact and less prone to breakage (Ao et al., 2019; Zhang et al., 2020).

As depicted in Figure 3, the covered yarns showed different failure modes with different twists. Taking K/K covered yarn for an example, the wrapping fiber and the core fiber broke at the same time when the twist was 100 twists/m, and the entire yarn eventually broke completely, as shown in Figure 3a. When the twist was 200 twists/m in Figure 3b, there were three types of tensile failure modes: First, the wrapping fiber and core fiber broke simultaneously; second, the wrapping fiber and core fiber broke at different time, the core fiber broke firstly, then the wrapping yarn broke; third, the core fiber broke firstly, then the wrapping fiber was straightened from the bent state without breaking. When the twist was 300 twists/m, the core fiber broke firstly while the wrapping fiber was only straightened from the

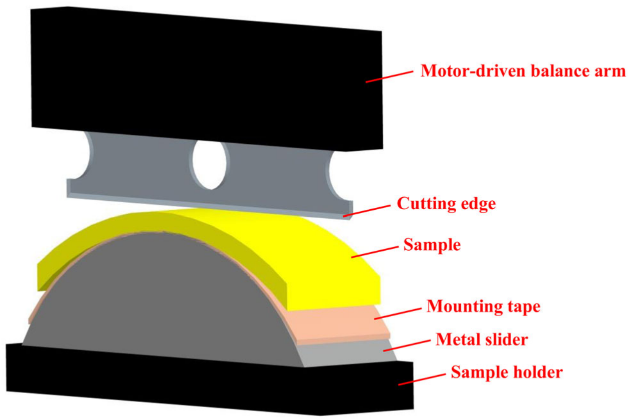


Figure 1. Schematic diagram of the cutting test.

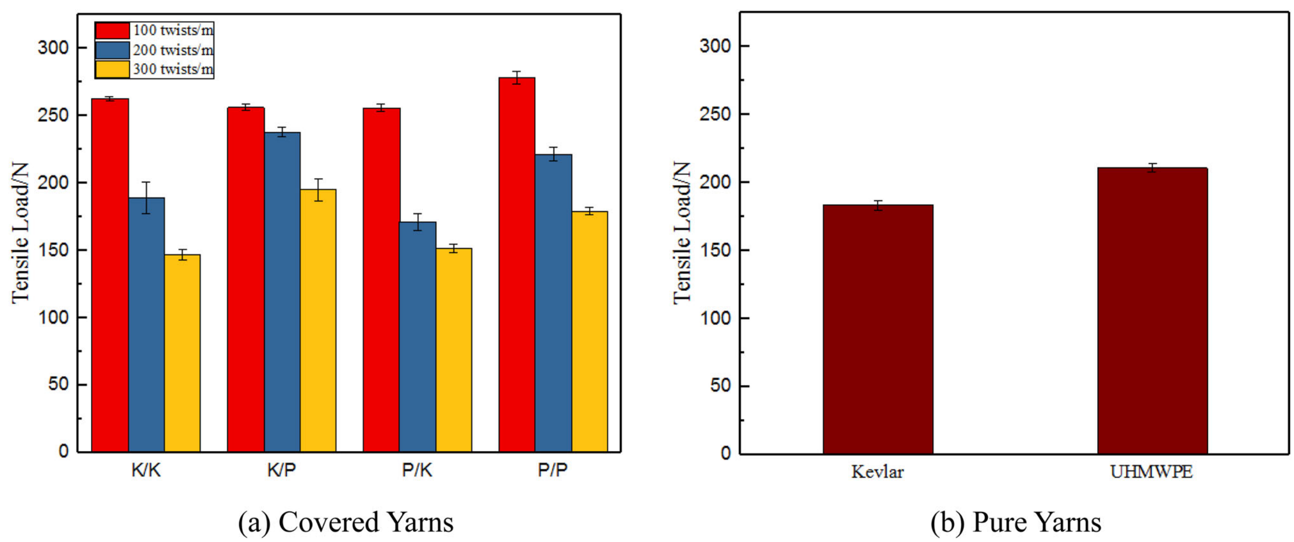


Figure 2. Tensile performance of covered yarns, pure Kevlar yarns and UHMWPE yarns.

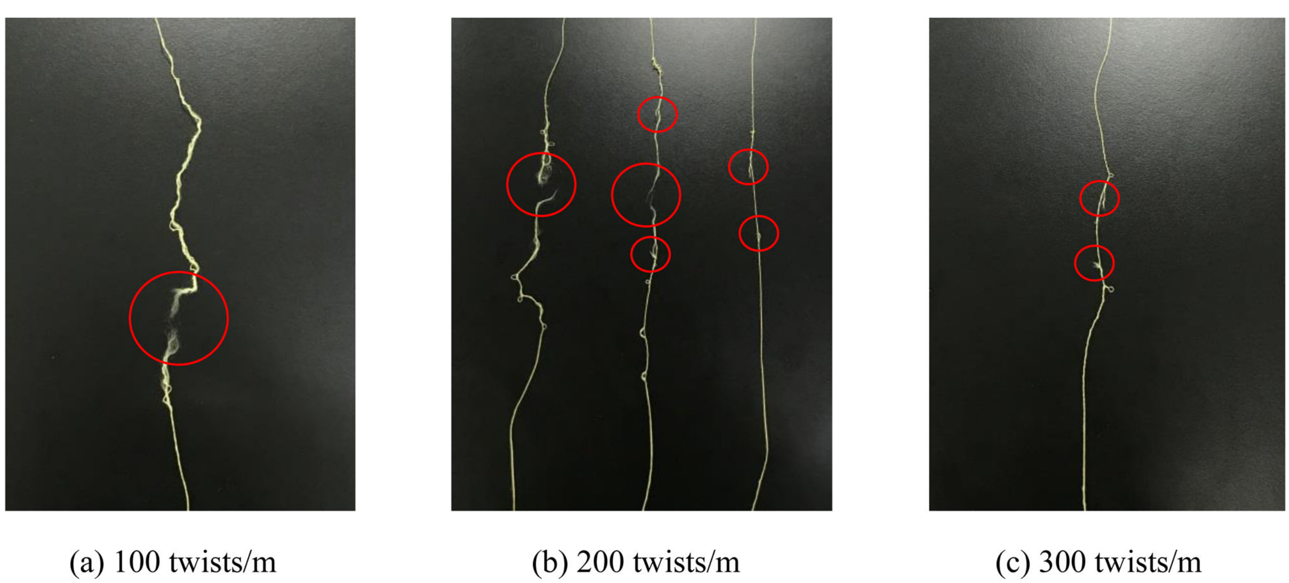
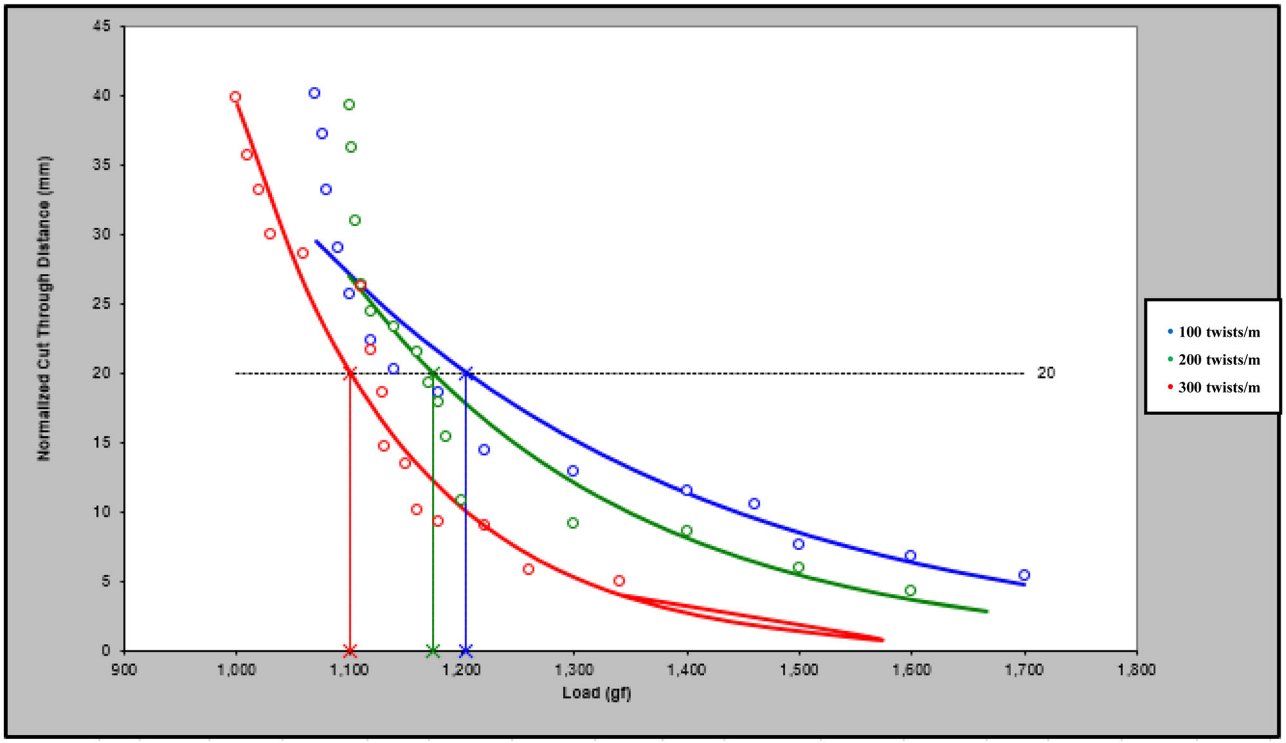
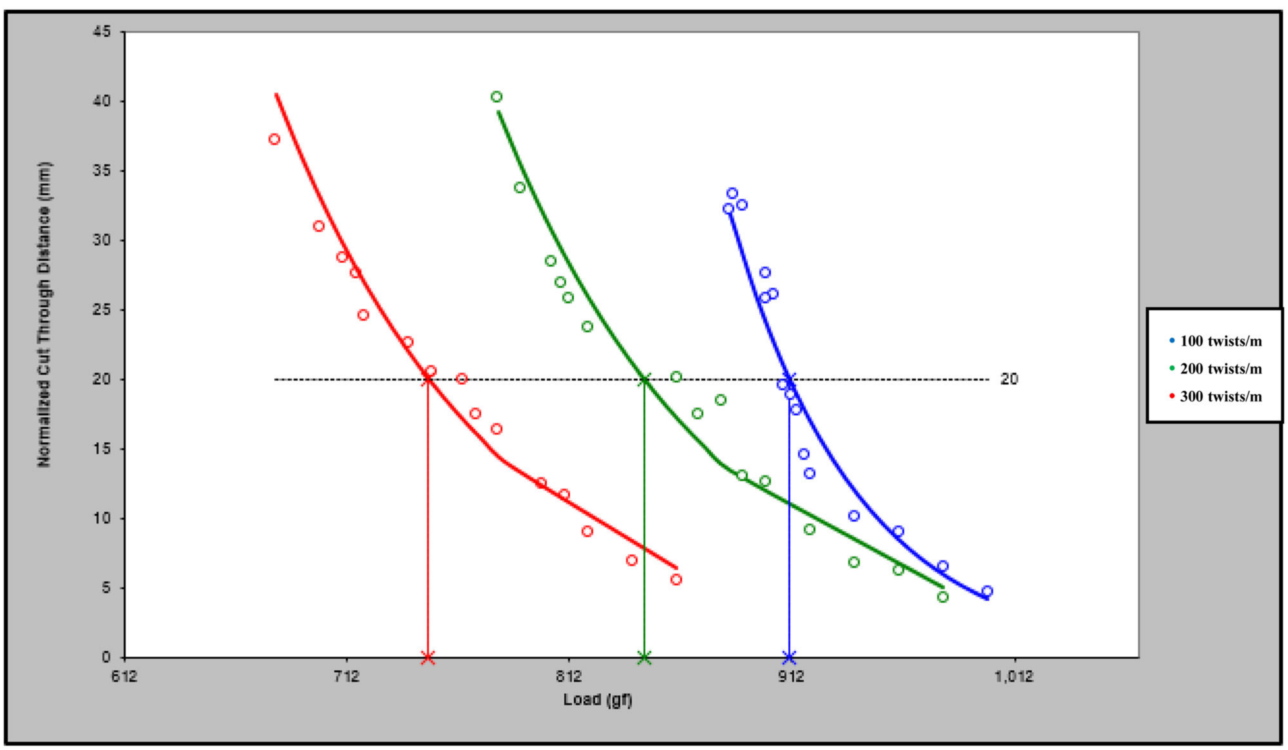


Figure 3. Influence of twists on the tensile performance of covered yarns (K/K covered yarns).



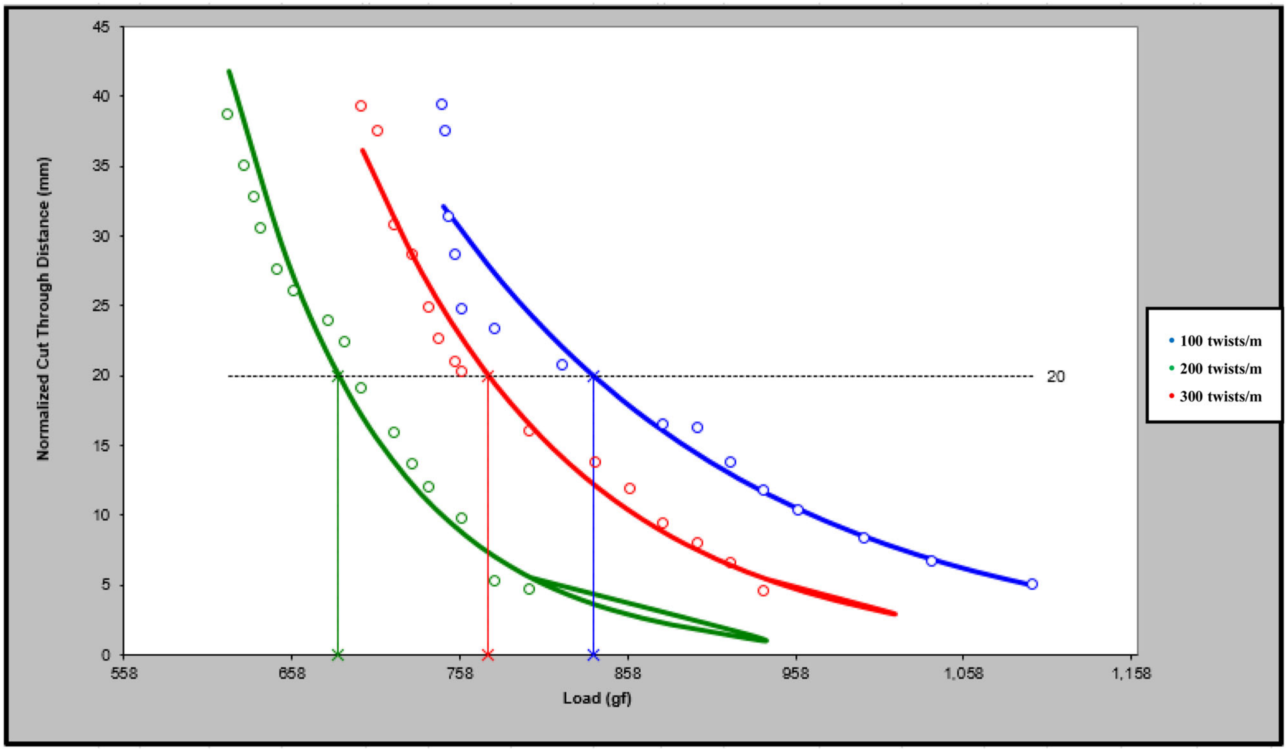
(a) K/K covered yarn fabrics



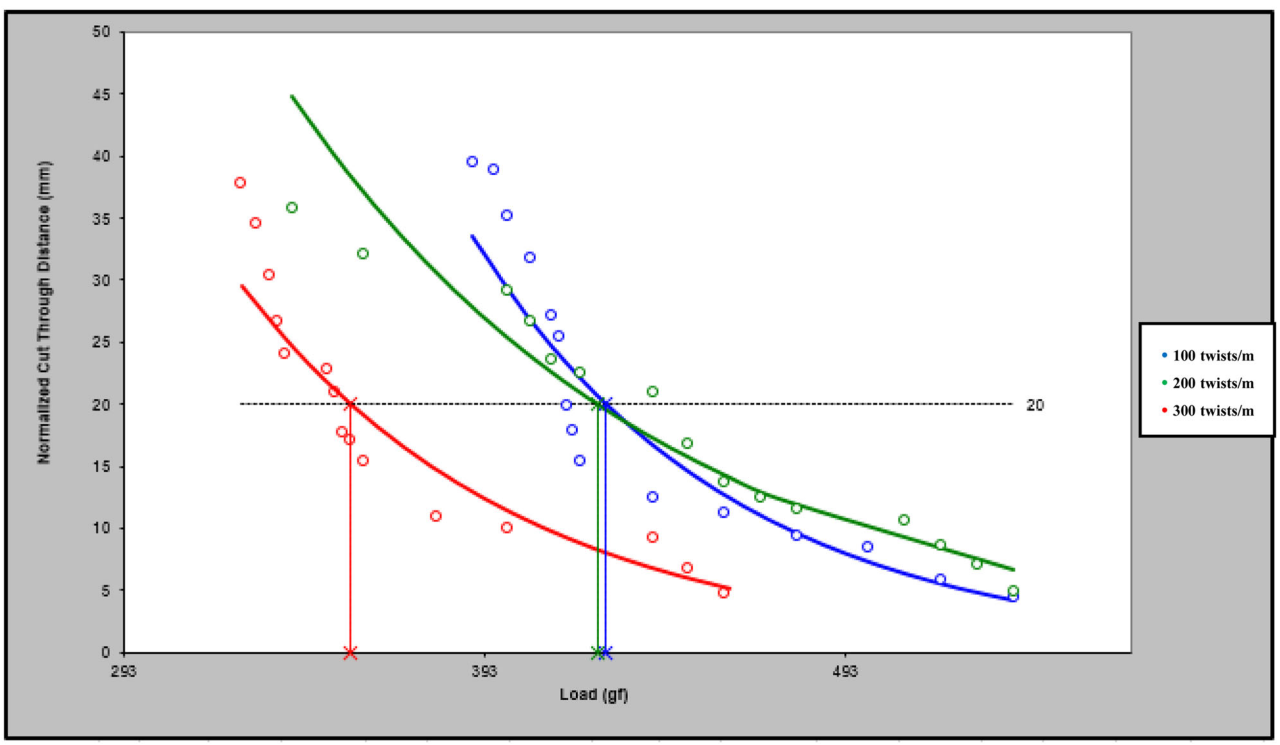
(b) K/P covered yarn fabrics

Figure 4. Cut-resistant performance of four kinds of covered yarn fabrics.

bent state without breaking, as shown in Figure 3c. The K/K covered yarns with the twists of 100 twists/m and 300 twists/m had uniform and stable tensile failure modes, so the values of CV were relatively small. The K/K covered yarns with the twists of 200 twists/m had various tensile failure modes, so tensile load was fluctuant and CV value was high.



(c) P/K covered yarn fabrics



(d) P/P covered yarn fabrics

Figure 4. Continued

3.2. Cut-resistant performance of covered yarn fabrics

The cut-resistant performance of four kinds of covered yarn fabrics, including K/K, K/P, P/K and P/P were shown in Figure 4a–d, respectively.

As seen from Figure 4a–d, the cut-resistant performance of the covered yarn fabrics decreased with the increase of twists of the covered yarns. This is due to the effect of twisting, which increases the cohesion force between the yarns, meanwhile, generates centripetal pressure between the fibers, which increases the friction between the fibers and prevents slippage. However, as the twists continue to increase, the pre-stress of the yarns increases, the axial distribution of strength of the fibers begins to weaken, the fiber are excessively inclined, the strength of the yarns decreases, the stored energy decreases, the ability to resist external force damage decreases, so cannot convert more cutting work into strain energy of yarns when damaged by cutting (Fang et al., 2015; Jiang et al., 2006; Liang et al., 2013).

Among the four different kinds of covered yarn structures, the ranking of cut-resistant performance of the fabrics was: K/K > K/P > P/K > P/P, as shown in Figure 4a–d. It demonstrated that the cut-resistant effect with Kevlar fibers wrapping around the core fibers was superior than that with UHMWPE fibers. This is related to the molecular structure of Kevlar and UHMWPE. There are a large number of amide groups and benzene rings on the molecular chain of Kevlar. The benzene rings are rigid structures and alternately arranged in the molecule, so that the molecular chains cannot rotate internally, and the molecular chains are closely packed together in an ordered state, showing a rigid linear structure. In addition, a π-π conjugated structure is formed between the benzene ring and the amide group, and hydrogen bonds are formed between the amide groups on the molecular chain, and the adjacent hydrogen bond planes are combined into crystalline grains by van der Waals force, which greatly improves the intermolecular interaction force. The molecular structure of UHMWPE is relatively simple. The main chain of the molecule is mainly composed of -CH_2-CH_2-, and there are no groups with greater rigidity. And there is no strong binding bond in the molecular chain. The intermolecular force is mainly van der Waals force, and the acting force is also relatively small. Therefore, under the action of external force, molecules are easy to slip (Chen, 2016; Si, 2015).

Taking K/K covered yarn fabric for an example, as shown in Figure 4a. The tensile load of the covered yarn was 262.7 N and the cut force of the covered yarn fabric was 1204.1gf when the twist was 100 twists/m; the tensile load was 189.3 N and the cut force was 1174.8gf when the twist was 200 twists/m; the tensile load was 147.0 N and the cut force was 1100.4gf when the twist was 300 twists/m. The results showed that there was a positive correlation between cut-resistant performance of the covered yarn fabrics and tensile strength of the covered yarns for the same kind of covered yarn structures. The reason can be explained that the cutting damage of the fabrics is mainly represented by the shear fracture of the yarns. In the condition of high twists, the initial shear force of the yarns is high, and the friction between the yarns is also large. The yarns are less prone to shear deformation to absorb a certain amount of energy. Therefore, the fabrics are more likely to break when the cutter is working (Tian et al., 2016; Zhu, 2013). In addition, the friction effect between the yarns increases with higher twists, leading to less mobility of the yarns in the fabrics. Meanwhile, the stretching of the yarns weakens, resulting in a reduction in the number of yarns subjected to cutting and a decrease in the cut-resistant performance of the fabrics (Tien et al., 2011; Yang, 2014).

Taking a twist of 100 twists/m for an example, as shown in Figure 4a–d, tensile load of P/P covered yarn was the highest, but the cut-resistant performance of P/P covered yarn fabrics was the worst. The results showed that there was no correlation between cut-resistant performance of the covered yarn fabrics and tensile strength of the covered yarns for the different kinds of covered yarn structures. It can be seen that the tensile performance of the covered yarns was not equivalent to the cut-resistant performance of the covered yarn fabrics. The tensile performance of the covered yarns was good, and the cut-resistant performance of the corresponding covered yarn fabrics was not necessarily good. This is related to the forced direction of the fibers are different under tension and cutting. When stretching, the fibers are stressed in the length direction. However, when cutting, the fibers are stressed in the circumferential direction. UHMWPE fibers have excellent longitudinal tensile properties, while worse transverse shear properties. It showed that the cut-resistant performance of the covered yarn fabrics was not only affected by the tensile strength of the covered yarns, but also the compositions of raw materials of the covered yarns and its molecular structure constituted a more critical factor.

Taking 100 twists/m covered yarn fabrics for an example, as shown in Figure 4a–d, the cut force of K/K covered yarn fabric was 1204.1gf, K/P covered yarn fabric was 910.8gf, P/K covered yarn fabric was 837.7gf, and P/P covered yarn fabric was 427.1gf. And the cut force of pure Kevlar fabric was 610.9gf in warp direction and 721.2gf in weft direction, while the value of pure UHMWPE fabric was 279.5gf and 381.1gf correspondingly (Tian et al., 2019). These results showed that cut-resistant performance of covered yarn fabrics were significantly better than that of pure Kevlar or UHMWPE fabrics.

4. Conclusions

Kevlar fiber and UHMWPE fiber were utilized to prepare twelve kinds of covered yarns, and covered yarn fabrics were prepared by using polyester filaments as warp yarns, covered yarns as weft yarns. Tensile performance of the covered yarns and cut-resistant performance of the covered yarn fabrics were evaluated. Some useful conclusions are drawn in this paper.

1. The tensile performance of the covered yarns are better than pure Kevlar or UHMWPE yarns with same linear density.
2. The tensile performance of four different structures of covered yarns decreases with the increase of twists.
3. The covered yarns show different failure modes with different twists.
4. The cut-resistant performance of covered yarn fabrics are significantly better than that of pure Kevlar or UHMWPE fabrics.
5. Among the four different kinds of covered yarn structures, the ranking of cut-resistant performance of the fabrics is: K/K > K/P > P/K > P/P. The cut-resistant

effect with Kevlar fibers wrapping around the core fibers is superior than that with UHMWPE fibers.

6. The cut-resistant performance of the covered yarn fabrics decreases with the increase of twists of the covered yarns.
7. For the same kind of covered yarn structures, there is a positive correlation between cut-resistant performance of the covered yarn fabrics and tensile strength of the covered yarns. However, no correlation is observed for different covered yarn structures.

Disclosure statement

No potential conflict of interest was reported by the authors.

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