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Study on the Multi-Directional Static Friction Properties of High Performance Yarns

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Abstract

To further optimise the bullet-proof performance of textile reinforced composites, multi-directional friction tests of aramid and ultra-high molecular weight polyethylene (UHMWPE) yarns were carried out by the slope method. The influence of the included angle between the high-performance yarns on the static friction coefficient for aramid and UHMWPE yarns was studied by measuring the friction coefficient. The relationship between the static friction coefficient and the included angle among the high-performance yarns was discussed. The results showed that the friction coefficient of aramid yarns was higher than that of UHMWPE yarns. Especially, at the same included angle between high-performance yarns, the static frictional coefficient of aramid yarns is 50% higher than that of UHMWPE yarns. In accordance with expectations, the static friction coefficient decreases with the increased included angle between high-performance yarns, and the included angle of high-performance yarns changes from 0º to 90º. The trend of rapid decline appeared when the included angle between high-performance yarns changed from 0º to 15º. For the actual result, the static friction coefficient of aramid and UHMWPE yarns is less than 0.3, which needs to be improved to increase the bullet-proof performance of textile composites.

Keywords

aramid, UHMWPE, static friction coefficient, included angle between high-performance yarns.

1. Introduction

Many researchers and producers favour high-performance yarns with high strength and high modulus in bullet-proof materials [1-3]. According to the different molecular structures, the high-performance fibers used for bullet-proof materials are divided into three categories, mainly including aramid fiber (Kevlar - DuPont and Twaron - Diren), ultra-high molecular weight polyethylene fiber (Dyneema - DSM), and polybenzoxazole (PBO) fiber (Zylon - Toyobo). These woven fabrics, which were woven with high-performance fibers, were used as reinforcements of bullet-proof materials, which effectively improved the bullet-proof performance and stability of the materials. Many researchers believe that the internal friction of yarn plays a crucial role in many factors affecting the bullet-proof and impact resistance of bullet-proof materials [4-6]. Motamedi [7] proposed that the higher the included angle between aramid yarns, the more bullet energy they absorb. It was expounded that the static friction coefficient of yarn plays a vital role in improving the bullet-proof performance of the fabric. To study the influence of the standard surface friction of aramid fiber on the bullet-proof properties of aramid fabric Boubaker [8] et al. established a micro model considering the internal friction of yarn to explore the impact resistance of aramid fabric reinforced bullet-proof materials. It was believed that the friction between aramid yarns led to the rigid reaction of the woven fabric, which was also the main factor for the excellent bullet-proof properties of bullet-proof materials based on aramid fiber. To further quantify the influence of the yarn friction coefficient on the bullet-proof performance of materials, Marcos [1,9,10] and others tested the friction coefficient of aramid yarns in woven fabrics through yarn drawing experiments. The best results of the bullet-proof performance of materials were obtained when the friction coefficient of yarn was 0.4.

For bullet-proof materials, research on the effect of fabric internal friction has a mature theoretical basis from experiment and theory. However, the bullet will change the orientation of high-performance fibers in penetrating materials, resulting in rotational friction between high-performance fibers. Due to rotational friction, the slip of yarn becomes smaller, and the fabric's rigidity larger. However, there have been few reports on the measurement of multi-directional friction between high-performance fibers, which have been limited to the fiber friction coefficient measurement method, proposed by Nils [11] in 1947, who measured the friction coefficient of wool and chemical fibers, making it possible to measure the single line friction coefficient. Afterwards, there was improvement in the measuring techniques and mechanical models, Gassara [12] developed a theoretical model to analyse the transverse friction coefficient between fibers. The model was based on measuring the friction coefficient of fibers in parallel, which was also the first attempt to measure the transverse friction performance of fibers.

The ballistic packets of bullet-proof vests should be made of fabrics with a geometric structure that ensures a maximum propagation velocity of the tension wave. In this scenario, the deformation region will be greater, which reduces the likelihood of local damage and the severity of the ballistic stroke on the user's body [13]. In this study,

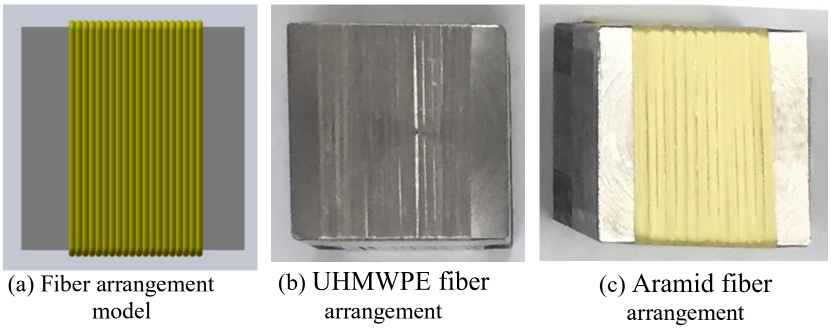

Fig. 1. Fiber arrangement of aramid and UHMWPE fibers on the cube surface

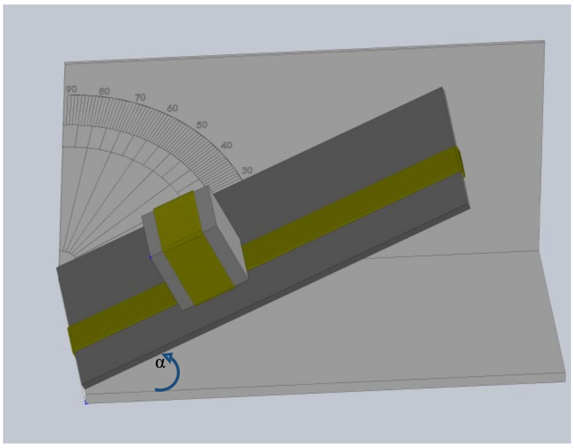

Fig. 2. Model of the slope board method

the reciprocal interaction of threads that created the fabric's interweaving significantly influenced its deformation, which was represented in simulations by using a model that directly depicted the fabric's sandwich structure. By means of the program ANSYS AUTODYN v.16, simulations were carried out utilising a precise technique for integrating motion equations as Twaron T750 layers were struck with a 9 mm parabellum FMJ (full metal jacket) bullet [14].

This paper uses the slope board method to conduct a multi-directional static friction test of aramid and UHMWPE yarns. In the test, the included angles of high-performance yarns were 0°, 15°, 30°, 45°, 60°, 75°, and 90°, respectively. The influence of the included angle between high-performance yarns on the static friction coefficient of aramid and UHMWPE yarns was studied by measuring the static friction coefficient of yarns at different included angles. Moreover, the relationship between the static friction coefficient of high-performance yarns and the included angle was discussed.

2. Experiment

2.1. Material selection and preparation

Yarns commonly used in bullet-proof materials: aramid 14 (Shandong Taihe New Material Co., Ltd.) and UHMWPE yarn (Hunan Zhongtai Chemical Fiber Products Co., Ltd.) were selected for this study, with a fineness of 1180 dtex and 200D, respectively, to measure the static friction coefficient of high-performance yarns.

In this experiment, the slope board method was used to measure the static friction coefficient of high-performance yarns. A total of 20 yarns were laid in parallel in a closed arrangement on a 20 mm×20 mm×20 mm square iron block to slide over a glass inclined plane, as shown in Figure 1.

2.2. Static friction coefficient (maximum coefficient of friction) test

A self-designed device was used based on the principle of sliding over an inclined plane for yarn static friction coefficient analysis, as given in Figure 2.

The basic working process is as follows: the cube iron block with a fixed bottom area was evenly covered with high-performance yarns, and the glass slope was also evenly covered with yarns. The sliding block was placed on the glass slope, and the angle "α", which was the plane inclination angle, was changed to make the sliding block start to slide. The tangent value at the moment when the sliding block starts to slide gives the static friction coefficient "μ_s". The test principle is shown in Figure 3.

The relationship between α and μ_s is as follows. Due to the action of the block gravity G, the block produces a downward force along the inclined plane:

$$G_1 = G \times \sin\alpha \quad (1)$$

Where; G - the gravity of the block [N], G_1 - the downward force along the inclined plane caused by the gravity of the block [N], α - the angle between the inclined and horizontal planes when the block begins to slide.

Gravity causes the block to produce pressure on the inclined plane, that is, the component force of gravity G_2:

$$G_2 = G \times \cos\alpha \quad (2)$$

Where: G_2 is the downward force of the vertical slope caused by the gravity of the block [N].

Due to the effect of G_2, there is friction between the parallel arrangement of high-performance yarn on the surface of the block and the yarn on the inclined plane.

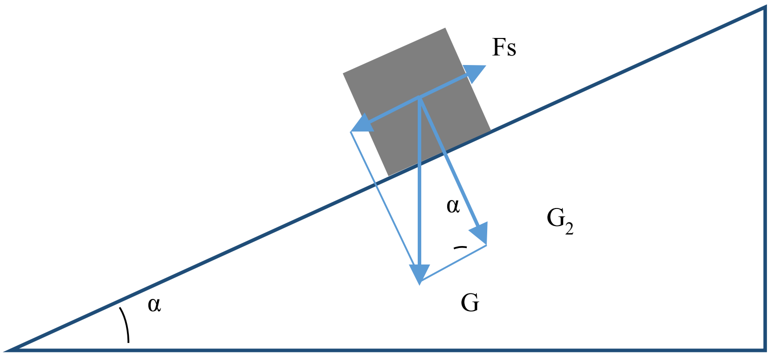

Fig. 3. Schematic diagram of the slope test

With the increasing angle of the inclined plane, the block begins to slide along the inclined plane, and the instantaneous friction is in balance with the downward force along the inclined plane caused by the gravity of the block;

$$G_1 = F_s \quad (3)$$

Where F_s is the static friction force between yarns, [N]. Equation 3 can be written as follows:

$$mgsin\alpha = \mu_s \, mgcos\alpha \quad (4)$$

Where m is the mass of the block, N; and μ_s is the static friction coefficient between the yarns.

$$\mu_s = mgsin\alpha / mgcos\alpha = tan\alpha \quad (5)$$

In order to clearly understand the multi-directional static friction coefficient μ_s of aramid and UHMWPE yarns, the included angles between the yarns were designed as follows: 0°, 15°, 30°, 45°, 60°, 75° and 90°.

3. Results and discussion

3.1. Influence of included angles between the yarns on the static friction coefficient of high performance yarns

Aramid yarn and UHMWPE yarn are the most common reinforcement materials in bullet-proof materials. In the process of bullet penetration, high-performance yarn will break and deviate in the yarn plane, resulting in a change in the angle between yarns. The friction between yarns significantly impacts the bullet-proof performance of materials. On this basis, the influence of the included angle between yarns on the static friction coefficient of high-performance yarn is analysed. The experimental results showed the relationship between the included angle and static friction coefficient (Figure 4).

The static friction coefficient of yarn under different included angles was measured; with five repetitions of the same test, shown in Figure 4. With the increase of the included angle, the static friction coefficient of the yarn becomes smaller. The static friction coefficient changes gently when the included angle is between 15° and 90°; that is, when the included angle changes from 15° to 90°, the static friction coefficient of the yarn decreases slowly; when the included angle changes from 0° to 15°, the static friction coefficient of the yarn decreases gradually. The results show that the static friction coefficient is largest when the yarns are parallel along the axial direction, which is much higher than the static friction coefficient of the other included angles between the yarns. The main reason for this phenomenon is closely related to the yarns' contact form and surface roughness. When two yarns are in parallel contact, the contact between them changes from point contact to line contact, and the roughness is also significantly improved. Therefore, when the included angle is 0°, the static frictional coefficient is much higher than for other included angles.

Both aramid and UHMWPE yarns show the same change trend, which indicates that the static friction coefficient of the yarn varies with a change in the included angle between yarns. The static friction coefficient is the largest when parallel friction occurs, and the smallest when vertical friction causes the included angle between yarns to be 90°. It mainly depends on the actual contact area between yarns. When the area is the largest, the number of rough peaks is the largest, and the static frictional coefficient is the largest.

3.2. Fitting analysis of included angle and static friction coefficient

The static friction coefficient of yarn at different angles presents a certain regularity, as shown in Figure 5. With an increasing included angle, the static friction coefficient shows a decreasing trend. According to the overall shape of the trend, it conforms to the exponential function form under specific conditions. Using the Origin nonlinear fitting function to fit the experimental data shows that the relationship between the static frictional coefficient μ_s of aramid and UHMWPE yarn and the yarn angle has the characteristics of a single increase in the inverse function. Therefore, the sigmoidal function is used to analyse the relationship between the static friction coefficient of aramid and UHMWPE yarn. The static friction coefficients of aramid and UHMWPE yarns are in accordance with the following functional relationship when the included angle is in the range of 0 ° to 90 °.

$$y = A_1 + \frac{A_2 - A_1}{1 + 10^{(Logx_0 - x)*p}} \quad (6)$$

Where A_1, A_2, $logx_0$ and p are the constrained sigmoidal function parameter values, and the exact parameter values of aramid and UHMWPE yarns are shown in Figure 5.

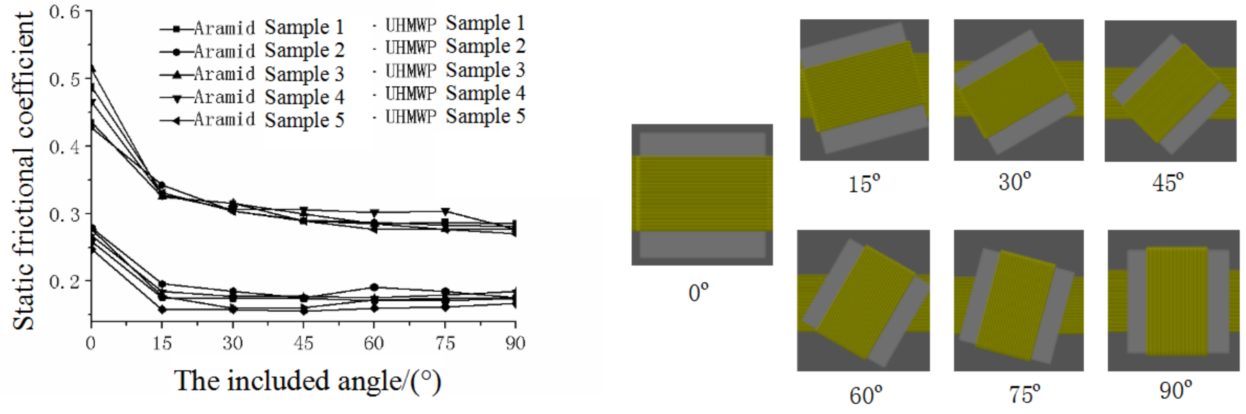

Fig. 4. Tendency of static friction coefficient with the included angle between yarns

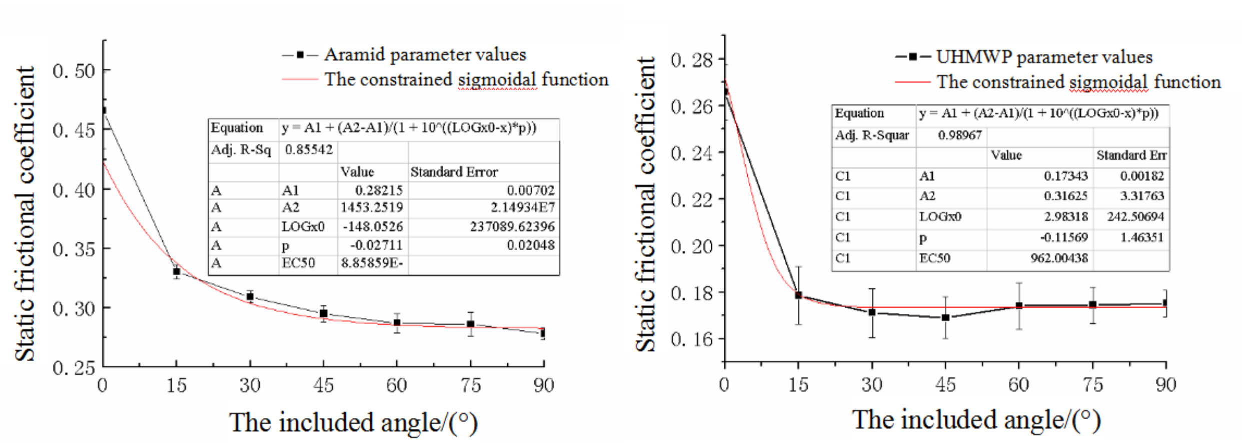

Fig. 5. Fitting of yarn static frictional coefficient with included angle between yarns

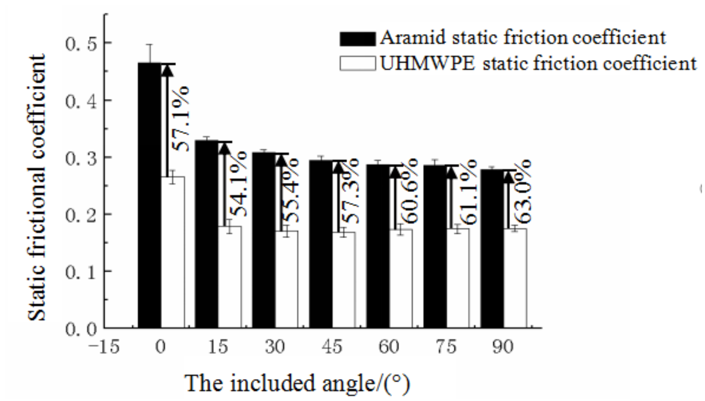

Fig. 6. Comparison of static friction coefficient between aramid and UHMWPE yarns

3.3. Comparative analysis of the static friction coefficient of aramid and UHMWPE yarns

Due to the difference in the material type, spinning process, and yarn fineness, the static friction coefficient of the two kinds of yarns is very different. The results of comparing the static friction coefficient of aramid yarn and UHMWPE yarn are shown in Figure 6. At the same included angle, the static friction coefficient of aramid yarn is much higher than that of UHMWPE yarn, which is increased by more than 50%. Especially, in the case of yarn vertical friction, the static friction coefficient of aramid yarn is 63% higher than that of UHMWPE. Thus, we speculate that the bullet-proof performance of aramid woven fabric reinforced bullet-proof material is higher than that of UHMWPE bullet-proof material under the same surface density. However, the static friction coefficient of aramid yarn is less than 0.3 under vertical friction, which is far less than the requirement of 0.4. When the yarns are in parallel friction, the static frictional coefficient of aramid yarn is higher than 0.4, but in the process of bullet-proof material and bullet penetration, for the high-performance yarn in the woven fabric material it is challenging to reach the state of parallel friction. Therefore, improving the static friction coefficient of bullet-proof material and the static friction coefficient under a certain included angle can effectively enhance the bullet-proof performance of the material.

4. Conclusion

To study the static friction coefficient μ_s of high-performance yarn under different angles, several friction tests were carried out on aramid yarn and UHMWPE yarn. In this research the static friction coefficient of aramid yarn and UHMWPE yarn with the included angle was studied, an sigmoidal function fitting analysis of the included yarn angle and static friction coefficient performed, and a comparison of the static friction coefficient of aramid yarn and UHMWPE yarn made.

(1) With the increase of the included angle, the static friction coefficient of the yarn decreases. When the included angle changes from 15° to 90°, the static friction coefficient of the yarn decreases slowly,whereas when the angle changes from 0° to 15°, the static friction coefficient decreases sharply.

(2) The relationship between the static friction coefficient of aramid and UHMWP yarns and the included yarn angle can lead to the development of and variation in the characteristics of the sigmoidal function. This model can preliminarily estimate the multi-directional static frictional coefficient μs of yarn.

(3) The static friction coefficient of aramid yarn is much higher than that of UHMWPE yarn. When the included yarns are at 90°, the static friction coefficients of both are less than 0.3. According to the optimal static friction coefficient of bullet-proof material, the static frictional coefficients of aramid and UHMWPE needs to be improved by a unique process.

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