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The role of twist on tensile and frictional characteristics of aramid filament yarns (AFYs)

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Abstract
In this study, the role of twist on the tensile and frictional characteristics of aramid filament yarns (AFYs) were systematically studied. The results revealed that the twist is incredibly crucial in optimizing the final properties of AFYs. It was found that the extension at break and the initial modulus had a high rise with the increase of the twist angle. Furthermore, an optimum twist value provided the maximum breaking strength of AFYs. Meanwhile, breaking strength emerged the tendency of enhancement firstly and then descended continuously till to the fracture of AFYs. In addition, it was inferred that the larger the twist angle, the more sharply the aramid filaments were drafted. In conclusion, if reasonably controlled, AFYs will emerge better tensile capability in axial direction, which are significant in actual industry use, especially in the field that sustained destructive power and constant friction.

1. Introduction

In recent years, with the big demand of high-performance materials in the field of industry, especially employed as soft armor against ballistic impact [1–3], as textile reinforced concrete [4, 5], and as protective equipment and aerofoil in the field of Aeronautics and Astronautics [6], respectively, aramid filament yarns (AFYs) are extensively used because of its excellent characteristics, such as softness, light weight, high modulus, high strength, excellent temperature resistance and etc.

In real-life applications, along with the extensively yielded of flexible materials, there are much more factors influencing the tensile and frictional properties of AFYs [7, 8], and two aspects that present articles primarily focus on, one is that AFYs were experimentally studied directly [9, 10] and the other is that researchers paid more attention to modelling representation [11]. For instance, some scholars researched the internal structure [12, 13] and the loading rate [14, 15] of AFYs, it was inferred that as a kind of initial force, friction force or sliding force plays a vital role in absorbing impact energy for various fabrics [16, 17]. In addition, there are many researches have investigated the difficulties of pull-out and the possibilities of fracture that AFYs may suffered when fabrics were used. The tensile and frictional parameters of AFYs deeply influenced the pull-out characteristics, bending property and stitchability of fabrics. Through the study of Guo and the colleagues [18], the yarns were pulled out easily if the load imposed away from the principal one.

As we all known, the filament material inside a core-spun yarn, with the ability to enhance resistance to the surrounding materials slippage against the core line at low twists, have positive effect on the strength of the yarn [19–21]. With the increase of the twists, the yarns broken in a similar way as the filament materials and other materials with the simultaneous rupture [22]. However, although some experiments were conducted when suffered from massive attack, the mechanism was not involved. Furthermore, the possibility of the damage or the strength inwards the destruction of the material was less studied in present papers.

Actually, the twist process is essential for produce, thus, researches on the tensile and frictional behaviors of AFYs are needful and urgent, and the role is also indispensable. Analyzing the role of twist versus tension and
friction is of great significance for fully utilizing the properties of AFYs. The purpose of this paper is to research the effect of twists on tensile and frictional characteristics of AFYs under destructive power and constant friction. The tensile and frictional performance tests were conducted after the AFYs were twisted by different twists and then the effect was analyzed systematically in this paper.

2. Experimental details

2.1. Fabrication of AFYs

In this study, the aramid filaments were developed by DuPont company and the twist procedure towards the selected aramid filaments was conducted by ZR98A twist test machine produced by Hangzhou Changyi Textile Machinery Co. Ltd. The twist factor are set from 0 to 300 with 20 gauge. As seen in figure 1(a), the aramid filaments were drawn by the drafting rollers and twisted in the twist triangle zone, then AFYs were formed and wound up on the bobbin. For the sake of fixing the structure of twisted and avoiding the appearance of untwist, the twisted AFYs need to be heat-set. The method of hot-air-set was employed, which heated the twisted AFYs with dry hot air in order to make the pattern fixed. The heat-set procedure was accomplished in YG747 Oven Device, which was produced by Changzhou Dahua Electronic Instrument Co. Ltd. After the experience of numerous pre-experiments, the heat-set temperature and the heat-set time should be controlled about 80 °C to 100 °C and 30 min, respectively. After above operations, the AFYs used in this paper were obtained, as seen in figure 1(b).

2.2. The tensile and frictional performance tests of twisted AFYs

The whole testing process was carried out in the constant temperature and humidity laboratory, the ambient temperature and relative humidity were (20 ± 2) °C and (65 ± 3)% respectively.

2.2.1. The tensile performance test

The tensile performance test was fulfilled by HD026N multifunctional electronic strength tester, as shown in figure 2(b), produced by Wenzhou Darong Textile Instrument Co. Ltd.

In the tensile test, the drawing rate and the pre-tension force were set as 100 mm per min and 0.2 N, respectively, and the gripping gauge was 200 mm. The test was conducted 10 times, and the results were averaged. In particular, the tensile performance test of AFYs is different from that of ordinary yarns, apart from larger strength characteristic, easy slipping is a special phenomenon in the stretching. As seen in figure 2(a), in order to solve this problem, the aramid filament samples were cut 300 mm at first, then the middle part was kept 200 mm, and the redundant length was adhered by antiskid felts with the length of 50 mm per side to prevent slippage.
2.2.2. The frictional performance test

The test of frictional performance was accomplished by LFY-110 yarn dynamic friction tester, as shown in figure 3(a), which was developed by Shandong Textile Research Institute.

Before the formal measurement, the AFY should be placed according to certain sequence that passing from bobbin under the assistance of guidance area 1 through many different leading and friction rollers (from A to I) in turn in the friction zone, and then through the guidance area 2 to the adsorption device as shown in figure 3(b), and at last the test started when pressing the control panel.

3. Results and discussion

3.1. The tensile properties

As we all known, the twist motion of torsion or intertwine imposed to the filament materials caused the section making a comparative rotation, the cohesive force increased stupendously because of the positive pressure from the interaction inwards filament materials which was the direct source of tangential friction resistance during the process of twist motion. That is to say, it was a complex process. Hence, twist factor with the symbol of $\alpha_{\text{tex}}$ was usually used to measure the twist degree of different yarns. However, if studying how the internal aramid filament bundles affect the AFY, the twist angle $\beta$, defined as the angle between the twisted aramid filaments and the axial of AFY used to estimate the twist degree of AFY, should be introduced.

For the purpose of researching the relationship between $\alpha_{\text{tex}}$ and $\beta$, the force analysis was modelled. As shown in figure 4(a), the shape transform of aramid filament $F$ was selected from AFY $Y$ to analyze, when the AFY was twisted by weak twist to $Y_1$ from its initial state $Y_0$, the form of the tracing aramid filament transformed...
from F0 to F1, and then with the shape of AFY transformed from Y1 to Y2 because of twisted strongly, the morphology of the tracing aramid filament was plotted as F2. It can be exposed that the AFY was elongated along the axial direction and the diameter shortened along the radial direction because of the twist motion. If defined $L$ and $d$ as the length and the diameter of AFY, $l$ as the length of aramid filament, respectively, then the relationships among the parameters were $L_{Y0} < L_{Y1} < L_{Y2}, d_{Y0} > d_{Y1} > d_{Y2},$ and $l_{Y0} < l_{Y1} < l_{Y2}$.

As shown in figure 4(b), for the purpose of analyzing the effect of the twist motion on AFY, one part of aramid filament with the shape F2 was elected. This part was spread out during one twist ($A \rightarrow K \rightarrow B$), right-angled triangle $\text{Rt} \Delta AOB$ was obtained with one side of the unfolded line and the other side of twist gauge in this one twist. According to the geometry relationship, formula (1) can be obtained.

$$\tan \beta = \frac{\pi d_Y}{L_{Y0}} = \frac{\pi d_Y}{100}$$

Where, $T_{\text{tex}}$ is the twist number in the length of 100 mm under the condition of tex and $d_Y$ is the twist gauge in one twist. Standard unit system is used for these parameters.

In the textile industry, the theoretical estimation formula of the diameter of AFY is as formula (2) [23].

$$d_Y = 0.03568 \sqrt{\frac{N_{\text{tex}}}{\delta_Y}}$$

Where, $N_{\text{tex}}$ is the tex defined as the gram weight of AFY in the length of 1000 m and $\delta_Y$ is the density of AFY.

Thus, plug formula (2) into formula (1), formula (3) can be got after calculation.

$$T_{\text{tex}} = 892 \sqrt{\frac{\delta_Y}{N_{\text{tex}}}} \cdot \tan \beta$$

In formula (3), for one definite AFY, $\delta_Y$ can be approximately affirmed to a constant value before and after twisted, however, the value of $N_{\text{tex}}$ will change, thus, in order to analyze the role of $\beta$, the form of formula (3) should be transformed into formula (4).

$$T_{\text{tex}} \cdot \sqrt{N_{\text{tex}}} = 892 \cdot \sqrt{\delta_Y} \cdot \tan \beta$$

For formula (4), parameter $\alpha_{\text{tex}}$ is introduced to express the twist degree of AFY during the process of the twist motion and command $\alpha_{\text{tex}} = T_{\text{tex}} \cdot \sqrt{N_{\text{tex}}}$, thus, formula (5) is obtained.

$$\alpha_{\text{tex}} = 892 \cdot \sqrt{\delta_Y} \cdot \tan \beta$$

It can be seen from formula (5) that $\alpha_{\text{tex}} \propto \tan \beta$ during the total process of the twist motion.

Herein, the value of $\delta_Y$ is 1.44 g cm$^{-3}$, thus, according to formula (5) and the values of $\alpha_{\text{tex}}$ given, the values of $\beta$ can be got, as seen in table 1.
With the values of $\beta$, the twisted AFYs tensile test curves of the indexes versus $\beta$, i.e. the strain $\varepsilon_Y$, the tension $\sigma_Y$ and the initial modulus $E_Y$, can be depicted in figure 5.

It can be seen from figure 5(a) that the values of $\varepsilon_Y$ augmented quickly at first and then rose steadily with the increase of $\beta$ until to the disruption of the AFYs. In addition, the values of $\varepsilon_Y$ were relatively small on the whole, which hesitated approximately over 3.1% and 3.8%. Compared to $\varepsilon_Y$, although the values of $\sigma_Y$ also emerged the tendency of enhancement with the arise of $\beta$ in the initial stage, however, when the increase added to a value, $\sigma_Y$ would descend continuously before the AFYs fractured, as seen in figure 5(b). Considering the index of $E_Y$, the values were all relatively tremendous, amplified firstly and then went up slowly even presented the trend of decline till to the broken of AFYs, as shown in figure 5(c).

As seen in figure 5(d), it was found that in the interior of every aramid filament there exists weak-links, and the fracture of aramid filaments almost occurred in the area of weak-links. For the facts that the AFYs consisted of lots of filament materials, it will cause asynchrony of the fracture towards the tensile force. When the value of $\beta$ was comparatively small, the function of the twist motion made aramid filaments close together and weakened the probability of the fracture in the area of weak-links. However, with the increase of $\beta$ value, the force of the twist motion would make some aramid filaments fracture in the area of weak-links, which emerged the results that the value of $\sigma_Y$ fell down dramatically in figure 5(b).

Furthermore, in order to get the function expressions, further analysis should be carried out. It’s supposed that the cause of this phenomenon may be relative with the morphology changes of aramid filaments and AFYs, thus, the function expressions of $\varepsilon$, $\sigma$ and $E$ were derived as follows.

Table 1. The corresponding values of $\alpha_{tex}$ and $\beta$.

| The parameters | The values |
|----------------|------------|
| $\alpha_{tex}$ | 0  20  40  60  80  100  120  140 |
| $\beta$ | 0.000  0.019  0.037  0.056  0.075  0.093  0.112  0.130 |
| $\alpha_{tex}$ | 160  180  200  220  240  260  280  300 |
| $\beta$ | 0.148  0.167  0.185  0.203  0.221  0.238  0.256  0.273 |

With the values of $\beta$, the twisted AFYs tensile test curves of the indexes versus $\beta$, i.e. the strain $\varepsilon_Y$, the tension $\sigma_Y$ and the initial modulus $E_Y$, can be depicted in figure 5.
On the basis of the analysis from figure 4(b), the change process of the tracing aramid filament, also the change of those parameters, was further studied with the shape from F1 to F2. As mentioned above, the twist motion is actually the shrinkage and extension along the direction of the diameter and the axis, respectively, as shown in the arrow mark (B11B12 and A11A12) in figure 6(a).

The geometry relationship between the aramid filament and AFY in any state can be obtained from the right-angled triangle RtΔAOB in figure 4(b), as seen in formula (6).

\[ l_F^2 = h_Y^2 + \pi^2 d_Y^2 \]  

(6)

The tracing aramid filament changed the shape from F1 to F2 with the morphology change from Y1 to Y2 by strong twist as plotted in figure 5(b). The twist angle of AFY changed from \( \beta_1 \) to \( \beta_2 \), as well. Similarly analyzed as mentioned above, the parts of aramid filament (C → P → D) and (E → Q → F) selected from F1 and F2 were spread out during one twist, respectively, right-angled triangle RtΔCOD and RtΔEOF were obtained with one side of the unfolded line and the other side of twist gauge in one twist. According to the geometry relationship, equation (7) can be obtained.

\[
\begin{align*}
\{dh_Y &= h_{Y1} - h_{Y2} \\
dl_F &= l_{Y1} - l_{Y2} \\
dd_Y &= d_{Y1} - d_{Y2}
\}
\]  

(7)

Where, \( dh_Y, dl_F, \) and \( dd_Y \) are the variation of the length and the diameter of AFY, and the length of the aramid filament before and after twisted, respectively.

According to the fact that AFY is very slender and the diameter is small, thus, the shrinkage along the direction of diameter is tiny compared to the variation from the direction of the length. It can be negligible from the variation value of the AFY diameter, so the limit of \( dd_Y \sim 0 \) was conducted. Formula (8) can be obtained after mathematics differential was applied to the two sides of formula (6) and \( (l_Fh_Y)^2 \) was divided.

\[
\frac{dl_F}{l_F} = \frac{h_Y^2}{l_F^2} \cdot \frac{dh_Y}{h_Y}
\]  

(8)

Furthermore, according to the strain defined formula expressions of aramid filament and AFY [24], equation (9) can be obtained.
Combined with formulas (7)–(9), formula (10) can be obtained.

$$\varepsilon_Y = \frac{\varepsilon_F}{\cos^2 \beta}$$  \hspace{1cm} (10)

As we known, $\varepsilon_F$ will rise and $\cos^2 \beta$ will become smaller with the increase of the degree of the twist motion, naturally, it can be calculated from formula (10) that $\varepsilon_Y$ will be larger, which identified by figure 5(a).

In addition, according to the Hooke’s law [25], formula (11) can be obtained.

$$\sigma_Y = E_Y \varepsilon_Y$$  \hspace{1cm} (11)

Plug formula (11) into formula (10), formula (12) can be got after calculation.

$$\sigma_Y = E_Y \frac{\varepsilon_F}{\cos^2 \beta}$$  \hspace{1cm} (12)

After above analysis, it can be inferred from formula (12) that the change of $\sigma_Y$ versus $\beta$ likes $E_Y$, but more severe, especially approaches to and after the critical value, just as seen in figure 5(b).

### 3.2. The frictional properties

In the light of the fact that interaction relationships between yarns and other bodies in actual process is very complex, especially along the axial direction, the theoretical analysis of the behaviors of frictional properties seems very essential. A microcell element of the twisted aramid filament was selected and force model was established as depicted in figure 7. Some parameters were set, i.e. $d_f, d_\beta, dT$ were the friction force, the twist angle, and the tight edge tension force of the microcell element.

According to the principle of force equilibrium [26], equation (13) was obtained.

$$\begin{cases}
    dN = T \sin \frac{d_\beta}{2} + (dT + T) \sin \frac{d_\beta}{2} \\
    T \cos \frac{d_\beta}{2} + df = (dT + T) \cos \frac{d_\beta}{2} \\
    df = \mu dN
\end{cases}$$  \hspace{1cm} (13)

Where, $T$ was the tension force of the two sides of the aramid filament, $dN$ was the positive pressure suffered by the microcell element and $\mu$ was the friction coefficient.

On account of mathematic principle, the limit of $d_\beta \sim 0$ was conducted, thus, $\sin \frac{d_\beta}{2} \sim \frac{d_\beta}{2}$, $\cos \frac{d_\beta}{2} \sim 1$, and $d_\beta dT \sim 0$. To sum up, formula (14) can be obtained.

![Figure 7. The force model of the twisted aramid filament.](image-url)
Formula (15) can be obtained after mathematics integral was applied to the left side from the force \( T_1 \) to \( T_2 \) and the right side from the twist angle 0 to \( \beta \) in formula (14).

\[
\frac{dT}{T} = \mu d\beta
\]

(14)

\[
\frac{T_2}{T_1} = e^{\mu \beta}
\]

(15)

Where, \( T_1 \) was the tension of the slack side, \( T_2 \) was the tension of the tight side.

Herein, \( \frac{T_2}{T_1} \) indicated the degree that the aramid filaments were drafted. Commanding \( K = \frac{T_2}{T_1} \), thus, formula (16) was obtained.

\[
K = e^{\mu \beta}
\]

(16)

As we all known, once a certain kind of material is affirmative, the value of \( \mu \) is known. Hence, it can be inferred from formula (16) that the index of \( K \) tended the growth with the increase of \( \beta \). Herein, the value of \( \mu \) is 0.33.

With the above analysis and the values of \( \beta \), the experimental and theoretical curves of \( K \) versus \( \beta \) can be depicted in figure 8.

It can be seen from figure 8 that the experimental values of \( K \) became larger with the increase of \( \beta \), which phenomenon was also verified by that of the theoretical ones. That is to say, the aramid filaments were drafted sharply with the increase of \( \beta \) until the AFYs broken.

4. Conclusions

In conclusion, the tensile and frictional characteristics of AFYs with different twists were theoretically and experimentally investigated in this paper. Firstly, twisted AFYs were prepared in different twist factors, and then the tensile and frictional performances of the twisted AFYs were tested. From the theoretical analysis and experimental results, it can be found that the values of \( \varepsilon_Y \) grew with the increase of \( \beta \) until to the disruption and relatively the values were small on the whole. Unlike \( \varepsilon_Y \), although the values of \( \sigma_Y \) also tended to increase with the arise of \( \beta \) in the initial stage, nevertheless, would descend continuously once the increase added to some extent before the AFYs fractured. Because the fact that the cohesive force of the aramid filaments became larger with the increase of \( \beta \), it told that the deformability of AFYs was difficulty. Hence, for the index of \( E_Y \), it was investigated that the values amplified till to the limit of the fracture and then went up slowly even presented the trend of decline. From the investigation of the frictional characteristic of AFYs, the aramid filaments were drafted sharply with the increase of \( \beta \) until the AFYs broken. To sum up, the twists of AFYs should be selected appropriately in actual industry use in order to gain better tensile capability in axial direction, especially in the field that sustained destructive power and constant friction.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).
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