The investigation of crimp and spin-finish effects on the processing behavior of polyaramide fibers during the spinning process

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Abstract. The spinning process optimization has been the subject of many articles and publications. They mainly study cohesion and friction forces presented as the most influential mechanical phenomena on fiber workability. However, they were limited to natural fibers studies and more specifically cotton. Therefore, and to enlarge these studies, this article focuses on the processing behavior of fire-resistant fibers of polyaramide type. Besides, inner fiber characteristics have a significant effect on their mechanical behavior. Consequently, the object of this article is to investigate the effect of fiber material and its characteristics, mainly spin-finish and crimp, on mechanical processing behavior, which includes fiber cohesion, and frictional resistance.

1. Introduction
Frictional and cohesive forces have been identified as the most influencing forces during the spinning process. They are the main mechanical phenomena affecting not only the homogeneity of the yarn but also its mechanical properties [1]. Add to that, the crimp is a parameter that affects both the opening of the floss and its workability. It is therefore important to determine the optimal crimp area for the workability of the polyaramide fiber. To that end, it is necessary to be sure about the measurement of the crimp’s degree.

This article focuses on two different batches of tests. The first one concerns the crimp measurement, and the second one the inter-fiber friction and cohesion analysis. The main aim of this study is to determine the optimum levels of crimp, cohesion and friction forces for better processing of polyaramide fibers.

Cohesion is defined as the force that is opposed to the relative movement between two distinct bodies in contact when no external normal forces are applied. On the other hand, external normal force, when applied between two bodies in contact, gives rise to some additional forces, called frictional ones, which equally are opposed to the relative motion of these bodies [2]. Generally, two types of friction forces have to be considered: static frictional force, just before the movement takes place, and dynamic one, which is generated during the movement.

When studying inter-fiber friction and cohesion forces, several parameters need to be considered, namely:
- The intrinsic characteristics of the fiber, including the nature and extent of the contact surfaces,
- The treatments applied to the fiber,
- The fibers arrangement in the tested sample. This parameter is not treated in the study, as the fibers are considered to be mostly aligned (sliver samples).

Friction is directly related to the surface properties and characteristics of the fiber. Gupta and El Mogahzy [3] divided the characteristics of the fiber into two categories: parameters related to the morphology of the surface of contact (surface nature, the presence of convolution, crimp ...) and those related to the surface junction’s properties depending on the chemical and physical structures of the fiber. It has been proved that the irregularity of the yarn increases with the friction force [4]. The main role of the latter is to limit the slippage between fibers by ensuring uniform linear distribution. This study [4] shows a correlation between the friction force and the tenacity of the yarn (between -0.56 and -0.74) which leads to thinking that the resistance of the yarn increases by decreasing the friction force. This can be explained by the possibility of mechanically damaging the fiber with high frictional force.

Unlike frictional forces, the cohesive ones increase the yarn homogeneity thus enhances its mechanical properties [4]. Cohesion is beneficial to fiber processing as it prevents the fiber flow’s breakage. As far as friction is concerned, very minimal values will not ensure a sufficient tenacity, whereas higher values give rise to fiber package slippery and irregularities.

2. Material and Methods
Different types of polyaramide fibers have been analyzed which include Conex, Kermel, Nomex, Yantai, etc... The fiber fineness is 1.7 or 2.2 dtex. The fibers were selected having a different level of crimp and spin-finish percentage, in the range of 10-26 and 0.32-1% respectively.

2.1. Crimp test
The measurement method is based on image analysis using laboratory software: Visilog 6.9. For each sample 3 parameters have been measured: the segment length, the range and the frequency (the number of patterns/cm), as shown in Figure 1.

![Crimp's parameters](image)

The theoretical frequency of the pattern was calculated using the following geometrical considerations made by segment length and range (Pythagoras theorem):

\[
f = \frac{1}{2\sqrt{s^2 - r^2}} \times 10
\]

Where:
f is the theoretical frequency (pattern/cm),
s is the segment length (mm),
r is the range (mm).

2.2. Friction and cohesion tests
17 samples were prepared using a laboratory sized carding machine model MDTA developed by Uster Technologies. It provides a sliver of 90 cm of length for 5 g of floss. The sliver was afterward divided
into smaller samples of 15 to 20 cm of length each. Every sample had a linear density of approximately 5.56 ktex.

The device used for this study (Figure 2) is a static friction tester (SFT). According to Nowrouzieh [5], it is composed of “two identical carriages. One of them (left) was fixed, whereas the second (right) was moving through a linear guide. A piece of sliver was put down in the channel of the two carriages, which were initially in zero displacement position i.e. the two carriages were in contact. The sliver was compressed with the upper carriage sides, where two identical weights were loaded. The moving one was tracked at a constant speed, whereas the fixed one was attached, by the intermediate of a force sensor, to the frame. The distance between the two carriages was measured by the displacement sensor”.

The sensor 100N has been used with a speed of 0.350 mm/s [5].

Figure 2. SFT device.

Figure 3. The usual friction curve [2].

Preliminary tests have shown that this speed, initially intended for cotton fibers, was also adequate for polyaramide fibers. The test finishes at a 90% break rate. The normal loads applied on the samples vary from 1 to 5 kg. Six tests have been carried for each load constituting 30 tests per sample.

Figure 3 shows the usual friction curve of a tested sample: In the first section AB the fibers are parallelized (elimination of the crimp) and elongated. The point B represents the friction force: it is the maximum force the sliver withstands at the beginning of the slip/slide of fibers with each other inside sliver and is a function of the total number of fibers. BC represents a stage during which the force slightly decreases. However, a small increase in strength is often noticed. This may be due to the overlapping of other forces: cohesion (for the fibers between the clamps and held by only one side), friction (for the fibers between the clamps and held only by the neighboring fibers) and the fiber sliding. Beyond the C point, sliver breakage takes place rapidly.

The results obtained from the SFT/MTS device give rise to the following equation:

\[
\frac{F}{N_f} = K \frac{W}{N_f} + C
\]

Where:
F is the frictional resistance force (cN) at point C (Figure 3),
W is the normal load applied to the fibers (cN),
Nf is the number of fiber in the sliver cross-section,
K is the friction coefficient,
C is the cohesion strength (cN).
PS: The friction strength for a normal load of 0 Kg is equivalent to a cohesion strength. This criterion allows deducing the cohesion strength from the friction test.

3. Results and discussion

3.1. Crimp test

The following table (Table 1) summarizes the results for all fiber types.
Table 1. Crimp test validation results.

| Sample     | Measured crimp |  | Theoretical crimp |  |
|------------|----------------|---|-------------------|---|
|            | Average        | Standard deviation | CI | Average        | Standard deviation | CI |
| 1 to 10    | 17.4           | 16.17                  | 4.6 | 16.3           | 21.07              | 6.0 |
| 11 to 13   | 26             | 2.72                  | 0.8 | 24.8           | 6.84               | 1.9 |
| 14 to 17   | 10.2           | 22.61                  | 6.4 | 12.4           | 8.98               | 2.6 |

A clear difference was observed between the crimp of the tested samples. One represents a higher crimp of the order of 26 while the other one does not exceed 10 (rounded). Samples with satisfying spinning behaviour show less crimp.

The statistic studies showed a high difference between the tested samples. This may be due to the number of used samples.

3.2. Friction and cohesion test

Figure 4 describes the curve frictional behavior of polyaramide fibers:

![Initial curve](image)

**Figure 4.** Friction curve: With and without spin-finish.

The stick-slip phenomenon (left) was observed during tests. It is particularly harmful to the spinning process. It affects the proper functioning of the production line (the speed of the machines) and the homogeneity of the produced material, and therefore the quality of the yarn.

As a first hypothesis, this phenomenon may be due to the spin-finish. Thus, it was necessary to test spin-finish-less fibers. No stick-slip was observed on this curve. Moreover, the friction parameters and the cohesive forces were calculated with and without spin-finish. All samples are of the same fiber and using the same spin-finish. The results are shown in Figure 5.

![Cohesion and Friction](image)

**Figure 5.** Spin-finish effect on cohesion and friction strength (blue for fibers without spin-finish, orange for fibers with spin-finish).
The spin-finish affects more friction force compared to the cohesive ones and decreases it by approximately 10 N. This result is observed for all sample types. The following table summarizes the found results:

Table 2. Cohesion and friction test results.

| Sample code | Crimp (1/cm) | Spinfinish rate (%) | Cohesion strength (cN/Tex) | K   |
|-------------|--------------|---------------------|-----------------------------|-----|
| 1           | 14           | 0.68                | 0.517                       | 0.75|
| 2           | 14           | 0.76                | 0.425                       | 0.82|
| 3           | 16           | 0.32                | 1                           | 0.74|
| 4           | 16           | 0.63                | 0.448                       | 0.81|
| 5           | 16           | 0.72                | 0.5                         | 0.81|
| 6           | 18           | 0.71                | 0.425                       | 0.82|
| 7           | 18           | 0.71                | 0.402                       | 0.74|
| 8           | 20           | 0.85                | 0.420                       | 0.86|
| 9           | 20           | 0.85                | 0.736                       | 0.78|
| 10          | 22           | 0.60                | 0.460                       | 0.81|
| 11          | 18           | 0.71                | 0.414                       | 0.82|
| 12          | 26           | 0.43                | 0.184                       | 1   |
| 13          | 26           | 0.61                | 0.701                       | 0.73|
| 14          | 10           | 0.81                | 0.529                       | 0.99|
| 15          | 12           | 1                   | 0.598                       | 0.85|
| 16          | 14           | 0.74                | 0.592                       | 0.95|
| 17          | 16           | 0.56                | 0.626                       | 0.84|

For samples 1 to 10, presenting a good spinning behavior, the cohesive force varies inversely with the spin-finish rate and crimp. Also, the spin-finish parameter seems more influential than the crimp on the inter-fiber cohesion. The friction parameter K varies in the same way with crimp and spin-finish rate. The latter parameter was found to be the more influencing one.

Add to that, the crimp seems to act more on the friction than on the inter-fiber cohesion.

4. Conclusion

Different polyaramide fibers presenting 17 variant samples were analyzed for this study. As far as the friction test is concerned, an unexpected phenomenon of stick-slip was highlighted for a particular commercial class of polyaramide fibers. The results show that it is due to the spin-finish rate. It is probably one of the origins of the fact that the tenacity of the fiber does not effectively affect one of the yarn.

For the second study, starting from the crimp 18, spinning problems start to appear. It seems that reducing the crimp up to less than 16 could help avoid these problems. Crimp seems to dominate the behavior of the polyaramide fiber for samples 14 to 17, while the spin-finish governs the ones from 1 to 11.

For a spin-finish rate of 0.3% the cohesion increases and reaches about 0.18 for a crimp value of 16. This corresponds to the "optimal" crimp level for the tested polyaramide (found above in the section
dedicated to the study of crimp). Therefore, the reduction in the spin-finish rate may optimize the response parameters. Therefore, a separated study of spin-finish (chemical nature and quantity) seems needed to complete these results. Add to that, it seems that the spin-finish limits the cohesion. This is clear with samples of a crimp 16 and a spin-finish rates higher than 0.56%.

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