APPLICATION REPORT

Manufacturing of filament yarns

Test methods for quality improvement

THE STANDARD FROM FIBER TO FABRIC
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1 Foreword

Filament yarns for textile and technical yarns have undergone a considerable development over the past 60 years. The production speed is now very high, and, therefore, a permanent quality management is required to keep the spinning process under control.

The two most important test methods to monitor the filament yarn spinning process are the measurement of the mass variation and the strength / elongation.

Uster Technologies has been manufacturing textile testing systems for measuring filament yarns since 1955. The evenness testers made in 1955 and the tensile testing systems for filament yarns have been considerably improved in the past 5 decades. The USTER® TESTER 5-C800 for filament yarns and the USTER® TENSORAPID 4 provide various tests results which are of enormous help for keeping the quality of the filament yarns on a constant level. The quality characteristics of filament yarns can be quickly assessed by means of these two testing systems. The test results can also be used to consider the consequences on subsequent processes.

This paper describes the opportunities of filament yarn testing with these two measuring systems for yarn evenness, strength and elongation.

2 Production processes for filament yarns

The production process for filament yarns depends on the raw material. The melt spinning process is used for polyester, polyamide, polypropylene and polyurethane filament yarns.

The dry spinning process is used for manufacturing acrylic and acetate fiber yarns.

The viscose process is used for manufacturing viscose and related filament yarns.

In chapter 3 we will concentrate on the melt spinning process because polyester filament yarns are the most important ones.
3 The melt spinning process

3.1 Determination of faults in the melt spinning process

Polyamide, polyester, polypropylene and polyurethane yarns are manufactured according to this process.

The localizing of faults with this spinning process is illustrated taking the example of the manufacture of polyester yarn manufacturing (Fig. 1).

**Hopper stage**

Chip hopper: storing and feeding of the polyester chips.

Extruder: Processing of the molten material
**Spinning stage**

Spinning head with gear pump and spinneret: the same amount of molten material is pressed through the orifices of the spinneret in the same amount of time.

Quench air duct: at a distance of 5 to 20 cm below the spinneret the filaments, spun from the molten material, are cooled by a jet of air and freeze. When using a multiple of orifices in the form of a spinneret, the bundle of filaments can then be drawn off as undrawn or partially drawn filament yarn.

The machine parts on the hopper stage, but also the gear pump and the quench air duct, produce long-term variations in the area of 20 to 1000 m if the parts are defective or the air stream in the quench air duct is not properly set.

**Wind-up**

Preparation: after leaving the quench air duct, the filament bundle is drawn over preparation rollers through an oil-fat-water emulsion.

Winding: The threads are wound on spinning packages. The yarn can be transported in this state to other processing machines.

All the elements below the spinning stage produce short-term variations if the parts are defective or worn out.

The machine parts below the quench air duct such as godets (if any), reversal mechanism of the winder, eccentric axis of the winder or eccentric packages produce short-term mass variations which have to be kept under control.

**4 Evenness testing of filament yarns**

**4.1 Numeric values of evenness**

Table 1 shows a selection of result columns of a filament yarn test. Yarn: Polyester, dtex 76f100. The test was carried out at 10 packages, test length was 1000 m per packages. The value U% is the evenness, the value CV% is the coefficient of variation of the yarn mass while the measuring system was set to “normal test”. The values CVm 1 m, 3 m, 10 m and 50 m represent the coefficient of variation of the yarn mass of various cut lengths.
Table 1
Numeric results of a filament yarn test

<table>
<thead>
<tr>
<th>Nr</th>
<th>U%</th>
<th>CVm 1m</th>
<th>CVm 3m</th>
<th>CVm 10m</th>
<th>CVm 50m</th>
<th>Rel. Count</th>
<th>mMin 1m</th>
<th>mMax 1m</th>
<th>mMin 10m</th>
<th>mMax 10m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/1</td>
<td>1.31</td>
<td>1.66</td>
<td>1.26</td>
<td>1.20</td>
<td>1.01</td>
<td>0.26</td>
<td>0.2</td>
<td>-3.5</td>
<td>3.8</td>
<td>-2.0</td>
</tr>
<tr>
<td>1/2</td>
<td>1.12</td>
<td>1.43</td>
<td>1.05</td>
<td>0.97</td>
<td>0.75</td>
<td>0.26</td>
<td>0.2</td>
<td>-3.3</td>
<td>3.4</td>
<td>-1.8</td>
</tr>
<tr>
<td>1/3</td>
<td>1.18</td>
<td>1.49</td>
<td>1.09</td>
<td>1.03</td>
<td>0.84</td>
<td>0.34</td>
<td>0.6</td>
<td>-3.1</td>
<td>3.6</td>
<td>-1.8</td>
</tr>
<tr>
<td>1/4</td>
<td>1.10</td>
<td>1.42</td>
<td>0.95</td>
<td>0.93</td>
<td>0.77</td>
<td>0.36</td>
<td>0.3</td>
<td>-3.2</td>
<td>3.3</td>
<td>-1.9</td>
</tr>
<tr>
<td>1/5</td>
<td>1.13</td>
<td>1.45</td>
<td>1.04</td>
<td>0.98</td>
<td>0.83</td>
<td>0.33</td>
<td>0.2</td>
<td>-3.3</td>
<td>3.4</td>
<td>-1.9</td>
</tr>
<tr>
<td>1/6</td>
<td>1.15</td>
<td>1.50</td>
<td>1.03</td>
<td>0.96</td>
<td>0.75</td>
<td>0.22</td>
<td>0.0</td>
<td>-3.1</td>
<td>3.4</td>
<td>-1.8</td>
</tr>
<tr>
<td>1/7</td>
<td>1.12</td>
<td>1.43</td>
<td>1.05</td>
<td>0.99</td>
<td>0.82</td>
<td>0.36</td>
<td>-0.1</td>
<td>-3.2</td>
<td>3.9</td>
<td>-2.1</td>
</tr>
<tr>
<td>1/8</td>
<td>1.13</td>
<td>1.43</td>
<td>1.13</td>
<td>1.06</td>
<td>0.83</td>
<td>0.26</td>
<td>-0.3</td>
<td>-3.6</td>
<td>3.9</td>
<td>-2.1</td>
</tr>
<tr>
<td>1/9</td>
<td>1.25</td>
<td>1.58</td>
<td>1.24</td>
<td>1.19</td>
<td>1.01</td>
<td>0.46</td>
<td>-0.1</td>
<td>-3.2</td>
<td>4.0</td>
<td>-2.2</td>
</tr>
<tr>
<td>1/10</td>
<td>1.21</td>
<td>1.54</td>
<td>1.15</td>
<td>1.07</td>
<td>0.91</td>
<td>0.30</td>
<td>-0.2</td>
<td>-3.6</td>
<td>4.9</td>
<td>-2.5</td>
</tr>
</tbody>
</table>

The column "Rel. Count" describes the relative fineness of yarn. The testing system calculates the mean of the yarn fineness for the entire measuring series and always prints out zero as a mean value. Afterwards, the system calculates the deviation of each individual package. The platform for this calculation is the capacitive measurement of the mass over the entire test length. The CV and s (standard deviation) represent the variation between the packages and Q₉₅% is the 95% confidence range. The values mMin and mMax describe the maximum deviation during the tests.

4.2 Diagram

The diagram provides an enormous amount of details on the spinning process for a filament yarn specialist. As the scale of the diagram can be magnified it is possible to demonstrate particular events in detail.
The mass variations of the filament yarn of Fig. 2 were produced in the quench air duct (Fig. 3).

A non-optimized air stream in the quench air duct is one of the most frequent sources of considerable mass variations of filament yarns. Since the take-off of filament yarns takes place at very high speed the cooling process in the quench air duct has to be efficient. If the air stream is not conducted properly the individual filaments start to vibrate. Since the filaments are not solidified yet at this point of the manufacturing process the vibrations cause mass variations.

Fig. 2 shows the diagram of the filament yarn whose numeric values are shown in Table 1.

Fig. 4 shows the same diagram where the red line represents the mass variation at a cut length of 1 m. It is as if the yarn was cut into pieces of 1 m and, afterwards, the variation between the pieces is determined.
4.3 Variance-length curve

The variance-length curve of a filament yarn can also be determined by a manual testing method. For this purpose the yarn is cut into pieces of a defined cut length. The longer the yarn pieces, the smaller is the variation between the individual yarn pieces (Fig. 5).

The red line in Fig. 5 shows an ideal filament yarn. The variance-length curve of an ideal filament yarn is a straight line in a diagram with double-logarithmic scales. If the filament yarn has long-term mass variations, the variations of the mass between the individual yarn pieces at 1 m, 2 m, 5 m, 10 m cut length are still high and, therefore, the black line in Fig. 5 is still far away from the ideal line.

Fig. 6 shows 10 variance-length curves of the yarn with the quality characteristics of Table 1. The diagram indicates significant variations up to about 20 m.
Deviations from the red line shown in Fig. 5 indicate manufacturing problems. The more the variance-length curve deviate in areas of long cut lengths the higher the long-term variation.

4.4 Spectrogram

The spectrogram indicates periodic or nearly-periodic mass variations. The spectrogram of an ideal filament yarn is a straight line which is close and parallel to the zero line (Fig. 7), because each irregularity has the same probability of occurrence. All spectrogram channels which lie higher than the ideal spectrogram indicate some manufacturing problems.

![Ideal spectrogram for filament yarns](Fig. 7)

The red line in Fig. 7 represents the ideal spectrogram.

Fig. 8 shows the spectrogram of the yarn described in Table 1.

![Spectrogram, filament yarn](Fig. 8)

The spectrogram shows a significant periodic fault with a wavelength of 1,2 m and a nearly-periodic fault between 10 and 80 m. It is the objective of the quality management in filament yarn manufacturing to approach the ideal spectrogram line of a filament yarn shown in Fig. 7 as good as possible. The strictly periodic fault with a wavelength of 1,2 m was produced at the winder (Fig. 1). This is a typical short-term fault. The visible deviation in the spectrogram between 10 and 100 m was explained in section 4.2.
Fig. 9 is the recording of 10 spectrograms of the yarn described in section 4.1. The 10 spectrograms show that the periodic faults are common to all packages.

Spectrograms of filament yarns frequently have many peaks which have to be interpreted correctly. Several peaks in the spectrogram do not necessarily mean that there are several manufacturing problems. The correct interpretation of the peaks, however, can provide detailed information where manufacturing problems exist [2].

Fig. 10 shows again a single spectrogram of the filament yarn described under section 4.1. In this case, however, it is the intention to describe the nearly-periodic mass variations. Fig. 10 shows the increase of the spectrogram in the range of 10 to 80 m. Such mass variations sometimes lead to misinterpretations if one only checks the diagram because the variations in the diagram look like strictly periodic faults (Fig. 2). Only the spectrogram shows precisely what is happening. This is a very frequent mass variation of filament yarns. The origin is a non-optimized air stream in the quench air duct as shown in Fig. 3.
4.5 Experience values

The filament yarns which were tested in the past 5 years in the laboratory of Uster Technologies have been evaluated in order to establish some experience values and benchmarks.

Fig. 11 shows experience values of filament yarn tests. It represents the evaluation of mass variations of various spinning packages. The position of the individual test in the benchmarks in Fig. 11 depends on mastering the spinning process and the fineness of the individual filaments. Very fine individual filaments (micro-filaments) in a filament bundle mostly lead to a slightly higher evenness.

Values below the 5%-line could only be reached by 5% of the filament yarn manufacturers.

Values below the 50%-line could only be reached by 50% of the filament yarn manufacturers, etc.

5 Strength testing of filament yarns

5.1 Numeric values of force and elongation

In the force-extension diagram shown in Fig. 12 the breaking force, force at rupture, breaking elongation and elongation at rupture are drawn in. The breaking force is the highest force value which is registered when carrying out a tensile test on a test sample. The breaking elongation is the elongation at the breaking force value. The force at rupture is that force which is registered immediately before the two ends of the test sample become separated from each other, and the elongation at rupture is the elongation at the force at rupture condition.
The USTER® TENSORAPID 4 determines, in its original version, the breaking force and corresponding breaking elongation.

In order to simplify a comparison between various raw materials, various spinning processes, various finishing methods and various yarn counts, it is more practical to combine the breaking force value with the yarn count. One obtains in this way a value which is practically independent of yarn count, the "Tenacity" (unit: N/tex). The USTER® TENSORAPID 4 also calculates the tenacity value.

In order to carry out the tests with the same measuring conditions it is very important that the same yarn count has to be entered prior to the test. The operator can distinguish between nominal count, mean of the measured count for a test series or the individual count for each bobbin or package. If tenacity values have to be compared it is always important to define what kind of count value was entered for the tenacity calculation.

5.2 Numeric values of work done

The work done can be represented graphically as the area contained by the force-extension diagram up to the point where the breaking force is reached.

In Fig. 13, the area corresponding to the work done is shown as shaded area. The work done can provide, particularly with respect to the subsequent processing of a yarn, directives indicating the suitability and reaction to subsequent processing conditions of the yarn concerned. It serves also as a means of making observations with respect to the raw material used and with respect to the spinning process.
The force-extension diagram and the work done do not describe the same characteristics but complement each other.

5.3 Stroke diagram

The stroke diagram of the USTER® TENSORAPID 4 is a graphical representation of the breaking force and the corresponding elongation of the single values. The stroke diagram provides primarily a visual reference to the variation of the single values as represented by the end points of the strokes (Fig. 14). One can therefore undertake an analysis, e.g., of the reasons for a large coefficient of variation value.

The lengths \( \ell_s \) and \( \ell_{1\text{cm}} \) are dependent on the test length and clamp positions. Per cm of yarn 40 strokes are printed out.
5.4 Frequency distribution diagram of force and elongation

One understands with frequency distribution diagrams the allocation and tracing out of measured values into separate classes. The frequency distribution diagram provides for a visual analysis of the position of the separate measured values, and a clear reference to extreme values and deviations from the normal distribution.

Fig. 15 and Fig. 16 show examples of frequency distribution diagrams of force and elongation.

The variations of the yarn force and elongation also generate wide frequency distribution diagrams (Fig. 15 and Fig. 16). The single values of the force lie between 1.25 and 2.50 N, those of the elongation between 3 and 6%.
5.5 Determination of elongation at a defined reduction of the breaking force

There are a number of yarns, particularly in the filament yarn sector, which have an extremely flat force-extension diagram in the region of breaking force (Fig. 17).

With such yarns, an extremely small change of force $\Delta F$ in the region of the breaking force can result in a large change of the elongation $\Delta E$. In such cases, the breaking elongation can vary over quite a wide range, even though the variation in breaking force is extremely small. Accordingly, with such types of yarns, it is difficult to obtain reproducible values of elongation. For this reason, one is interested in determining, in such special cases, the elongation at some point on the force-extension diagram at which better and more reproducible values are possible.

In Fig. 18 a point on the force-extension diagram has been chosen which lies at the position $0.9 \ F_H$ after the point of breaking force has been passed. The elongation in reference to this point is $E_{0.9 \ F_H}$.

The USTER® TENSORAPID 4 can determine the elongation values for any chosen point on the force-extension diagram after passing the position of breaking force and down to the value $0.1 \ F_H$. 

Fig. 17
Flat force-extension diagram in the area of the breaking force $F_H$
Example: If the elongation is determined at 0,9 FH, the work done can still be calculated for the shaded area in (Fig. 18).

5.6 Determination of reference points

With the USTER® TENSORAPID 4, the force or elongation values can be determined according to a choice of freely chosen points on the force-extension diagram.

Fig. 19 shows, as an example, a force-extension diagram for a filament yarn. From the characteristic points A, B, C and D, one is interested in both force and elongation because these two values contribute a great deal towards an understanding of the manufacturing process, i.e., a change of the points indicates a change of the manufacturing parameters.

In order to find these points, the tensile force values FA to FD can be entered into the testing instrument. The testing instrument provides, correspondingly, the respective elongation values, or the elongation values can be entered into the testing instrument and the corresponding tensile force values obtained.
5.7 Force-extension diagrams of filament yarns

The relationship between force and elongation depends considerably on the raw material. In addition, there is also a difference between undrawn, partially drawn and drawn filament yarns.

100% polyester, monofilament, 21 tex / Diagram on right side: mean of the test series

The characteristic force-extension diagrams show a strong non-linearity and a wide variation of the elongation at maximum force which spans a range of 25 to 45%.

100% polyester, POY (partially oriented yarn), dtex130f144

A flow range can be recognized between 3 and 40% elongation. In this area the application of higher force on the yarn only results in higher elongation. The area of yarn breaks lies between 100 and 135%.

100% polyester, FDY (fully drawn yarn), dtex82f36

The characteristics of this material are the non-linearity between force and elongation and a large variation of the breaking elongation.
100% polyamide 6, undrawn, dtex105f17
Polyamide 6 shows a step-wise break of the individual filaments.

100% polypropylene, 200 tex
This yarn shows a wide variation of the elongation at maximum force.

100% polyurethane, 50 tex
Fig. 25 shows a flat force-extension diagram till 250% elongation. Afterwards, the force is increasing drastically and reached its peak at about 350 to 400%. The breaking elongation varies over a wide range.

100% glass fiber yarn, 70 tex
Glass fiber yarns are characterized by its high force and very small elongation.
5.8 List of numeric and graphic results which can be selected

<table>
<thead>
<tr>
<th>Numeric results</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breaking force</td>
<td>Highest force value which occurs during the strength test</td>
</tr>
<tr>
<td>Breaking elongation</td>
<td>Elongation value at highest force value (in %)</td>
</tr>
<tr>
<td>Testing time</td>
<td>Time starting from pretension to highest force value</td>
</tr>
<tr>
<td>Tenacity</td>
<td>Highest force value divided by the count or the cross-section</td>
</tr>
<tr>
<td>Work done to break</td>
<td>Work represented by the area below the force-extension diagram starting at pretension and ending at breaking force</td>
</tr>
<tr>
<td>Part work</td>
<td>Work represented by the area below the force-extension diagram between two defined elongation values</td>
</tr>
<tr>
<td>Reference values (max. 10)</td>
<td>Forces at selected elongation values or elongations at selected force values</td>
</tr>
<tr>
<td>E(F-)</td>
<td>Elongation after exceeding the breaking force. This elongation value can be selected in the range of zero (breaking force) to –90% of the breaking force (see also section 5.5).</td>
</tr>
<tr>
<td>F(1.Br.)</td>
<td>Force at which the first filament breaks</td>
</tr>
<tr>
<td>Modulus values (max. 10)</td>
<td>Secant or tangent modulus at selected elongation values</td>
</tr>
<tr>
<td>Chord modulus</td>
<td>Secant modulus at selected force values</td>
</tr>
<tr>
<td>Yield point</td>
<td>Point at the end of the elastic range of a filament yarn</td>
</tr>
<tr>
<td>Yield Load</td>
<td>Force value at the end of the elastic range of a filament yarn</td>
</tr>
<tr>
<td>Yield Stress</td>
<td>Tenacity referred to the count or the cross-section at the end of the elastic range of a filament yarn</td>
</tr>
<tr>
<td>Yield Strain</td>
<td>Elongation at which the elastic range of a filament yarn ends</td>
</tr>
<tr>
<td>Natural draw ratio</td>
<td>Point at the end of the flow range</td>
</tr>
<tr>
<td>NDR-Load</td>
<td>Force at the end of the flow range</td>
</tr>
<tr>
<td>NDR-Stress</td>
<td>Tenacity referred to the count or the cross-section at the end of the flow range</td>
</tr>
<tr>
<td>NDR-Extension</td>
<td>Elongation at the end of the flow range</td>
</tr>
<tr>
<td>NDR-Ratio</td>
<td>Ratio between NDR extension and Yield strain</td>
</tr>
</tbody>
</table>

Table 2 Result options, strength tester
<table>
<thead>
<tr>
<th>Graphic results</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke diagram of strength and elongation</td>
<td>This diagram represents the strength and elongation graphically so that the type of variation can be detected easily</td>
</tr>
<tr>
<td>Force-extension diagram</td>
<td>This diagram shows the relationship between force and extension</td>
</tr>
<tr>
<td>Histogram of strength and elongation</td>
<td>The histogram shows the distribution of the individual test results. Of particular interest in strength testing are the weakest values.</td>
</tr>
<tr>
<td>Modulus-extension diagram</td>
<td>This diagram shows the relationship between the modulus and the extension</td>
</tr>
<tr>
<td>Scatter plot</td>
<td>This diagram particularly shows the outliers among the tested specimens or single tests</td>
</tr>
<tr>
<td>Spectrogram of force and elongation</td>
<td>Determination of periodic force and elongation values by means of a spectrogram</td>
</tr>
<tr>
<td>Relaxation</td>
<td>The yarn specimen is extended until a predetermined force is reached. Afterwards, the elongation is kept constant and the reduction of the force is measured over a defined period.</td>
</tr>
<tr>
<td>Retardation</td>
<td>A force is applied on the specimen until a predetermined elongation is reached. Afterwards, the force is kept constant and the increase of the elongation is measured over a defined period.</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>A load is applied on a specimen from a lower to an upper elongation value and, afterwards, the same process is repeated several times (Fatigue tests). The change of the elongation is measured after a defined number of cycles.</td>
</tr>
</tbody>
</table>

Table 3
Result options, strength tester
6 Practical examples, evenness testing

6.1 Defect of the gear pump

A defective gear pump in the melt spinning process generates long-term periodic variations, particularly if a tooth of the gear pump is defective. This is an example of a long-term variation.

Fig. 27 shows the diagram of this filament yarn with a significant fault. In this case the specialist who has to interpret the fault with a repetition of about 130 m has to know that such a fault is located must be above the spinneret.

![Long-term periodic variation](image)

6.2 Quality problems with monofilament yarn suppliers

The manufacturing of monofilament yarns requires a stable process, because the unevenness at a certain position cannot be compensated by other filaments. Therefore, measures are taken to establish constant conditions during the spinning process.

The following are the results of the unevenness and strength/elongation of two suppliers to a monofilament knitter. The raw material was polyamide (PA6), count 55 dtex (49.5 denier).

Supplier A

The table of the numeric test results shows that the variation of the unevenness is high and reaches a level of 1.96% after 10 measurements. The unevenness of a monofilament yarn (CVm) should be below 1%.

The count variation (Rel. Cnt±) in Table 4 shows values from -3.3% to +3.5%, which is significant for a monofilament yarn.
Due to the high count variation the coefficient of variation with a cut length of 50 m (CV₅₀₅ₐ₉) is still 1.22%.

The diagrams, Fig. 28, demonstrate that the spinning process is not under control and explain the high count variation. The total yarn length per diagram is 1000 m.

A second production line of the same supplier shows that the 10 tests at one package are more stable with a coefficient of variation CVₘ = 0.96% (Table 5). However, the count (Rel. Cnt±) still varies from -1.9% to +2.3%.

The coefficient of variation at a cut length of 50 m is only CVₘ = 0.48%.
The diagrams only show little mass variations (Fig. 29).

The spectrograms of the 10 measurements at the same package demonstrate that periodic mass variations are still available.
The stroke diagrams of the elongation, Fig. 31, demonstrate that the elongation values are not stable as expected.

![Fig. 31](image1)

**Supplier B**

Table 6 represents a monofilament of the same count, but of a different supplier. The coefficient of variation of the mass (CV_{m}) is 2.37% which is very high for a filament yarn. However, the mass variation at a cut length of 50 m (CV_{50m}) is extremely low (0.21%). The count variation is also excellent (Rel. Cnt±) from -0.7% to +0.6%.

![Table 6](image2)

The diagrams, Fig. 32, demonstrate the quality problem. It is a periodic mass variation with a wavelength (repetition rate) of about 10 m.

![Fig. 32](image3)
The spectrograms, Fig. 33, of the 10 tests demonstrate the periodicities with a repetition of about 10 m (no strict periodicity).

The stroke diagram of the elongation, Fig. 34, shows the effect of the periodicity on the elongation. The peaks in the stroke diagram of elongation are the result of the periodic mass variation mentioned above.

**Conclusion**

The low monofilament yarn quality of the suppliers A and B have resulted in a bad reputation of the knitter who has used the monofilaments for particular industrial applications. It has resulted in frequent holes and in a bad appearance of the finished fabric. Both suppliers have to improve their manufacturing process considerably. For such improvement processes the evenness and strength testers are very helpful.

**7 Literature cited**

