Research Article

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A simple method for measuring the monofilament diameter of continuous filament yarn with high bending stiffness via synthetic laser imaging

Abstract: The uniformity of the monofilament diameter plays a key role in the performance of continuous filament yarns and their subsequent products. However, traditional methods for measuring fiber or filament diameters focus on estimating the arithmetic mean data, and only part of the diameter data can be obtained. Additionally, most of these traditional methods require complex sample preparations, such as by making cross-sectional slice samples. This study intends to present a simple method for measuring almost all of the monofilament diameters in a single yarn. It is not necessary to make slice samples. After the yarn sample or fabric sample is taken and prepared, synthetic laser images can be obtained directly by scanning the cross section of the sample with a 3D laser scanning confocal microscope. According to the results of many experiments, more than 90% of the monofilament diameters of a single yarn can be measured. The result also shows that the difference in the diameter data between the traditional method and the synthetic laser imaging method is less than 2%. This method presents the differences between the majority of monofilament diameters, and the yarn clustering property can be evaluated by the sum of the monofilament diameters and the yarn cross-sectional area.

Keywords: continuous filament yarn, yarn cross section, monofilament diameter, glass yarn, high bending stiffness yarn

1 Introduction

Continuous filament yarns consist of several monofilaments arranged in the same direction with similar diameters. The uniformity of the monofilament diameters plays a key role in the performance of continuous filament yarns [1]. Therefore, the measurement of monofilament diameters is very important to the quality of continuous filament yarns and their subsequent products [2].

There are several methods of measuring fiber diameters. The methods based on cross-sectional slice samples include Hardy’s slice method, the resin embedding method [3], and the scanning electron microscope method [4]. These methods usually require the preparation of cross-sectional slice samples using Hardy’s slicer or an ultra-thin slicer. Processing slice samples requires skilled operation and takes a long time. Even so, it is not always successful, and sometimes several samples require repeated processing. The other methods are not based on cross-sectional slice samples, and they include the projection microscopy method, the optical fiber diameter analyzer method [5–7], the single fiber analyzer method [8,9], the Sirolan laserscan method [10,11], the cutting and weighing method [12], the airflow instrument method [13–15], the acoustic measurement method [16], and the level set and fast marching method [17,18]. However, these methods cannot obtain diameter data for every fiber in a single yarn, and their operations are cumbersome, time-consuming, and laborious.

For continuous filament yarns, in the glass fiber industry for example, the measurement of fiber diameters generally refers to “ISO 1888:2006 Textile glass – Staple fibers or filaments – Determination of average diameter.” This standard specifies two methods for measuring the diameters of glass fibers, the longitudinal profile method and the transverse section method. The longitudinal profile method requires impregnating a bunch of fibers in a mounting fluid such as benzyl alcohol, methyl salicylate, or a mixture of one part glycerol and two parts of water.
Then, 25 readings of longitudinal profiles on randomly selected fibers are obtained using a microscope with an overall magnification of at least 400, and preferably 1,000. The arithmetic mean of the 25 measurements is taken as the measurement result. If the fiber bundles cannot be separated from each other in the mounting fluid, they need to be burned off to bare glass at 625°C in a muffle furnace. The transverse section method requires curing the fiber bundles in the mold with a fast-curing polyester or epoxide resin. After the resin is hardened, the upper surface of the molding body is polished with a polishing device, and then a thin disc (about 4 mm thick) is cut from the top of the molding with a saw. Diameter measurements are then made on 25 discs taken at random over the specimen by a microscope with an overall magnification of 400–1,000 as mentioned above, and the arithmetic mean of the 25 measurements is then calculated. Both of these methods focus on estimating the arithmetic mean data of the fiber diameters, and the 25 pieces of data are based on random portions of fibers. Furthermore, some data might be from measuring one identical fiber repeatedly. Even if more data is measured by these methods, it is scarcely possible to further obtain the diameters and distributions of all the fibers in a single yarn.

Laser scanning is also used in another method of measuring fiber diameters, namely, the Sirolan laserscan method, but it is essentially different from the method mentioned in this article. The measurement principle of Sirolan laserscan is the suspension of short fibers about 2 mm in length in a mixture of isopropanol and distilled water. When the liquid passes through the measuring tank, the fibers pass through and block the laser beam one by one, so that the intensity of the laser beam changes. By measuring the peak voltage of the detector’s electric signal, the measurement data is converted into fiber diameter data through computer processing [10,11]. It is a longitudinal measurement method of the fiber diameter. However, there is no guarantee that all of the fibers in a single yarn will be measured, and the diameter of each fiber can be obtained intuitively. Therefore, it is not representative of a characterization of a fiber diameter distribution. In contrast, the simple method mentioned in this article achieves simplicity and quickness in the aspect of sample preparation. The most important thing is that more than 90% of the monofilament diameter data of a single yarn can be measured expeditiously and it presents the differences and uniformity of a majority of the monofilament diameters.

This study presents an efficient and convenient method for measuring the diameters of almost all the monofilaments in a single yarn. It is not necessary to make cross-sectional slice samples, but it rather involves processing yarn samples or fabric samples by simple preparation methods first. Then, synthetic laser images can be obtained by scanning the cross sections of the samples directly with a laser confocal microscope before the diameter data is quickly measured using image analysis software. The differences between the monofilament diameters are then compared, and the distribution of the monofilament diameters is obtained. In previous methods, only a small amount of fiber diameter and mean data could be obtained. However, this method can solve the problems associated with complex preparations, difficult operations, low efficiency and high costs. It can also help filament yarn factories quickly find problems and control monofilament diameters effectively in production. As a result, the uniformity of monofilament diameters can be improved and continuous filament yarns’ quality and subsequent products’ stability can be improved as well.

2 Experiment

The raw material used in the experiment is C1200 glass yarn, a kind of continuous filament yarn with a high bending stiffness. The experimental instruments include a Keyence VK-X110 laser scanning confocal microscope, ceramic scissors, double-sided adhesive tape, and glass slides. The microscope uses a red semiconductor laser with a wavelength of 661 nm. The software used in the experiment includes Image-Pro Plus, Excel, and SPSS.

2.1 Method for yarn sample preparation

It is necessary to prepare the yarn samples in order to observe the yarn cross sections stably under a laser confocal microscope. First, the pieces of glass yarn which have not been woven yet are taken from the yarn bobbins. Yarn samples are taken every 10,000 m, 25 mm each time, and 5–10 times for each bobbin. Then, the glass yarn is stuck flat on the double-sided adhesive tape. Next a small piece of the double-sided adhesive tape with the yarn sample along the vertical yarn direction is cut with the ceramic scissors. Then, this piece of tape is clamped vertically using two glass slides. When the yarn cross section at the cut of the tape is stably placed under the lens of laser confocal microscope, the preparation of the single yarn sample is completed, as shown in Figure 1.
This method for yarn sample preparation is only applicable to continuous filament yarns with high bending stiffness, and ceramic scissors with sharp edges should be used. In this way, the cut yarn samples have neat cross sections, so as to ensure that clear synthetic laser images can be obtained. However, for ordinary staple yarns or filament yarns with low bending stiffness, the Hardy’s slice method or resin embedding method should still be used to prepare the yarn cross section slices.

\[2.2\] Method for fabric sample preparation

Better experimental results can be obtained by using the yarn samples woven in the fabric as the objects of observation. The preparation of yarn samples woven in the fabric does not require the double-sided adhesive tape. Because the yarn woven in the fabric is constrained by other yarns, the fabric samples can be easily held by the glass slides and most importantly, the yarn woven in the fabric has better yarn integrity properties, which means it is not spread easily. First, a small piece of woven glass fabric is cut with ceramic scissors. In order to meet the demands concerning the measuring warp or weft yarn, a single warp or weft yarn is removed. Similar to the operation of the double-sided adhesive tape in the yarn sample preparation method as mentioned above, one end of the fabric without removed yarns is clamped vertically with two glass slides. Then, the yarn cross section at the end of the fabric with removed yarns is stably placed under the lens of laser confocal microscope and the preparation of the fabric sample is completed, as shown in Figure 2.

Similar to the method for yarn sample preparation, this method for fabric sample preparation is only applicable to woven fabrics with high bending stiffness filament yarns, and ceramic scissors should also be used. For the fabric samples made of staple yarns or filament yarns with low bending stiffness, clear synthetic laser images of the yarn cross sections cannot be obtained using this method for fabric sample preparation.

In most cases, the measurement data from monofilament diameters acquired using the fabric samples can be more accurate than those of monofilament diameters acquired using the yarn samples. This is because the yarn from fabric samples, especially warp yarn, has passed through sizing and other pre-weaving preparation processes, and is constrained by other yarns in the meantime. Therefore, using yarn samples from fabrics for experiments is suggested. If it is inconvenient to obtain fabric samples, a single yarn from a glass strand cake or glass bobbin can still be used for the experiments.

\[2.3\] Synthetic laser image acquisition

One of the advantages of laser scanning is that the images from different depths of field can be synthesized together. Therefore, it is not necessary to worry about the
measurement errors caused by the different heights of the cross sections of each monofilament. On the contrary, the accuracy of direct measurement by optical microscopy is lower than laser scanning due to unavoidable depth of field problems.

The magnifications of the VK-X110 laser confocal microscope are 200, 400, 1,000, and 2,000 times, respectively, of the original lens. Also, it can magnify digitally up to 16,000 times, but the image definition will decrease when digital magnification is used. The monofilament diameter of C1200 glass yarn is about several microns, so it needs to be magnified at least 1,000 times to obtain better images. Clear images of monofilaments cannot be obtained directly with ordinary optical lenses at 1,000 times or more, so laser confocal microscopes are used to obtain clear synthetic laser images.

First, a 200 times magnification lens is used to locate the sample by adjusting the X–Y platform of the laser confocal microscope. Then, the focal length is adjusted to make the cross-sectional images of most of the monofilaments as clear as possible. Then, a 400 times magnification lens is switched to for further magnification, and the X–Y platform is adjusted a little in order to align the field of vision to the center of the glass yarn. At that time, it is scarcely possible to ensure the clarity of the cross-sectional images of all the monofilaments. The focal length should be adjusted during the switching of the lens. Finally, a 1,000 times magnification lens is switched to, and it is difficult to find clear cross-sectional images of each monofilament with the optical lens. Only small parts of the cross sections of monofilaments can be identified. However, the effect of the laser scanning will not be impacted as long as each monofilament in the glass yarn is within the field of vision.

The upper limit position and lower limit position should be determined before laser scanning. The autofocus function is invalid at such a time. Therefore, the focal length should be adjusted manually to find the upper limit position and lower limit position of the depth of field that makes each monofilament’s cross section visible. Meanwhile, other parameters such as the pitch distance, image resolution, precision, and brightness are set. The pitch distance in the Z-direction is 0.13 μm, the image resolution is 2,048 × 1,536, and the brightness is 7,880. Because the pitch distance in the Z-direction is far lower than the monofilament diameter, the Z-direction resolution can be guaranteed. Therefore, the accuracy of the synthetic laser images is reliable. The approximate scanning time is calculated by the viewer software automatically, and then the laser scanning begins. After synthesis, clear laser images of cross sections of C1200 glass yarn are obtained, as shown in Figure 3.

### 2.4 Monofilament diameter measurement

The image analysis software Image-Pro Plus is used to measure the monofilament diameters. The synthetic laser images of cross sections of C1200 glass yarn are imported into the software. Then, the Count/Size tool in the measurement module is started. The measurement object is selected first, and it is set as Diameter (max), namely, the maximum diameter option, in order to determine the maximum diameter within a single outlined area. Some necessary settings are set in the custom options setting at this point. For example, the outline style is set to Outline, the label style is set to Object #, the label color is set to Green, the option “Dark background on sample” is chosen, and the object option is set to 4-Connect [19]. The outline of the synthetic laser image can be automatically recorded after setting it up. The background of the synthetic laser image is black, and the cross section of the glass yarn is white, so the automatic bright object count option is chosen.

Then, the image recognized by the image analysis software and the results of the measurement data are obtained, as shown in Figure 4. The measurement data...
of the maximum diameter $D_{\text{max}}$ is sorted from large to small. When a specified number in the target area is selected, the software will automatically prompt the location of the outline on the image. Here some necessary work is done, such as checking the diameter data and determining the range of the maximum and minimum data.

Then, some necessary image processing work needs to be implemented, such as using the “Remove Holes” tool to remove small outlines from large outlines, as shown in Figure 5(a). Another important process is splitting objects. When two or more monofilaments are adjacent to each other, the cross-sectional image of such monofilaments are recognized as being one large outline area. Therefore, the Auto-split tool is used to separate them into single outline areas, in order to ensure the accuracy of the $D_{\text{max}}$ data. If the diameter data is obviously too large, it shows that the outline area probably still contains more than one monofilament, which can be split manually, as shown in Figure 5(b). The largest piece of diameter data corresponds to an independent outline area of one monofilament, indicating that there is no adjacent outline. The diameter data downward is reliable.

It should be noted that the cross-sectional image of one monofilament is not necessarily a complete circle. Because when $D_{\text{max}}$ is used as the measurement object, the diameter data obtained is valid as long as the cross-sectional image is more than half a circle [20]. Similarly, the $D_{\text{max}}$ data is also invalid when it is smaller than a certain value. It is probably redundant data generated in image recognition. While an outline area is less than half of a completed circle, all smaller pieces of diameter data can be deleted. The remaining data is the effective diameter data of each monofilament. All of the diameter data can be validated using manual measurements tool in the measurement module.

3 Results

After all the monofilament diameter data for the yarn is measured, many statistical data results can be obtained and analyzed, such as the mean value, the sum value, the maximum value, the minimum value, the standard deviation, and the coefficient of variation. This statistical data can reflect the differences between monofilament diameters and the uniformity of monofilament diameters in the yarn, so as to determine whether the yarn meets the specified quality standards.

The original $D_{\text{max}}$ data measured in Image-Pro Plus is the data of the pixel points. All the data is imported into Excel and based on the scale of the synthetic laser image, the original data of the pixel points is converted into the actual monofilament diameter data in microns, as shown in equation (1):

$$d_i = \frac{D_{\text{max}}m_s}{n_p},$$

where $d_i$ is the actual monofilament diameter (μm); $D_{\text{max}}$ is the original data of the maximum diameter; $m_s$ is the length of the measuring scale; and $n_p$ is the number of pixels of the measuring scale in the image.

In order to improve the accuracy of analyses, the yarn sampling interval should be at least 100 m, at least 5 samplings should be conducted to record the monofilament diameter data of a yarn, and the average monofilament diameter should be calculated according to equation (2):
where \( \bar{d} \) is the average monofilament diameter (\( \mu m \)); \( n \) is the number of monofilaments, which is determined according to the number of measurement results; and \( d_i \) (\( i = 1, 2, 3, \cdots, n \)) is the actual monofilament diameter (\( \mu m \)).

The standard deviation \( s^* \) of the monofilament diameter is:

\[
 s^* = \sqrt{\frac{\sum_{i=1}^{n} (d_i - \bar{d})^2}{n}}.
\]  

Assuming the diameters of all monofilaments obey the normal distribution, and the confidence probability is 95%, that is, \( a = 0.05 \), the maximum estimated value of the monofilament diameter is:

\[
d_{\text{max}} = \bar{d} + t_{a}(n-1) \frac{s^*}{\sqrt{n}}.
\]  

where \( t_{a}(n-1) \) is the \( t \)-distribution function with the degree of freedom \( n - 1 \) and the upper quantile \( a \).

The minimum estimated value of the monofilament diameter is:

\[
d_{\text{min}} = \bar{d} - t_{a}(n-1) \frac{s^*}{\sqrt{n}}.
\]

Generally, smaller monofilament diameters result in higher yarn strengths and better yarn quality. To check whether a tested monofilament diameter meets the requirements of standard diameters or nominal diameters, the \( t \)-test is adopted, and the statistic \( T \) is calculated according to equation (6):

\[
 T = d_0 - t_{a}(n-1) \frac{s^*}{\sqrt{n}}.
\]

where \( d_0 \) is the nominal monofilament diameter.

If \( \bar{d} \leq T \), the tested monofilament diameter is considered to be less than or equal to the nominal diameter. Otherwise, \( \bar{d} > T \), the tested monofilament diameter is considered to be greater than the nominal diameter.

Generally, the number of monofilaments is greater than 60, \( a = 0.05 \), and \( t_{0.05}(60) \approx t_{0.05}(60) = 1.645 \).

### Table 1: Monofilament diameter statistics of three types of yarns

| Yarn type | Method                              | \( d_0 \) (\( \mu m \)) | \( n \) | \( \bar{d} \) (\( \mu m \)) | \( d_{\text{max}} \) (\( \mu m \)) | \( d_{\text{min}} \) (\( \mu m \)) | \( s^* \) | \( T \) | \( c_r \) (%) |
|-----------|-------------------------------------|--------------------------|-------|---------------------------|-----------------------------------|-----------------------------------|---------|-------|-----------|
| C1200     | Transverse section method           | 4.4                      | 50    | 4.79                      | 5.25                              | 4.22                              | 0.323   | 4.32  | 6.74      |
|           | Synthetic laser imaging method      | 530                      | 530   | 4.88                      | 5.35                              | 4.14                              | 0.296   | 4.38  | 6.07      |
| D900      | Transverse section method           | 5.3                      | 50    | 5.47                      | 6.08                              | 4.95                              | 0.268   | 5.24  | 4.90      |
|           | Synthetic laser imaging method      | 727                      | 727   | 5.49                      | 6.36                              | 4.59                              | 0.421   | 5.27  | 7.67      |
| BC1500    | Transverse section method           | 4.0                      | 50    | 4.43                      | 5.23                              | 3.78                              | 0.395   | 3.91  | 8.92      |
|           | Synthetic laser imaging method      | 514                      | 514   | 4.42                      | 5.35                              | 3.63                              | 0.412   | 3.97  | 9.32      |

Figure 6: Monofilament diameter distribution for C1200 glass yarn.
The monofilament diameter uniformity is expressed by the monofilament diameter coefficient of variation \( c_v \), which is calculated according to equation (7):

\[
    c_v = \frac{s}{d} \times 100\%.
\]  

(7)

According to the above data calculation, the monofilament diameters of C1200, D900, and BC1500 glass yarns are measured using the transverse section method in ISO 1888:2006 and the synthetic laser imaging method, and the statistical data shown in Table 1 are obtained.

It can be seen from Table 1 that the average difference of the monofilament diameters measured by the two methods is less than 2%, while the range of estimation of monofilament diameters by the synthetic laser imaging method is a little larger. The results show that the data obtained by the synthetic laser imaging method are more comprehensive, and can more accurately reflect a majority of monofilament diameters in a single yarn.

Additionally, the distribution maps for the monofilament diameter data are easily obtained, as shown in Figures 6–8. As references for horizontal comparison, these maps show the monofilament diameter distribution for C1200, D900, and BC1500 glass yarns. From these maps, it can be found that the monofilament diameter distribution of different yarn types is not consistent. Compared with the calculation of the average value of 25 fiber diameters, this method provides more complete and

Figure 7: Monofilament diameter distribution for D900 glass yarn.

Figure 8: Monofilament diameter distribution for BC1500 glass yarn.
intuitive information for the distribution of the monofilament diameter of a single yarn, and thus is more advantageous than the transverse section method in ISO 1888:2006.

According to the results of many experiments, generally more than 90 pieces of monofilament diameter data can be obtained from a single yarn containing 100 monofilaments. This represents satisfactory reliability and validity. The yarn quality can be monitored effectively via prompt feedback regarding the differences between monofilament diameters and their distribution. Then, the uniformity of the monofilament diameter can be controlled via process adjustment, and the continuous filament yarns’ quality and subsequent products’ stability can be improved.

4 Discussion

(1) According to the monofilament diameter measured by the synthetic laser imaging method, the cross-sectional area of each monofilament can be calculated. Meanwhile, the cross-sectional area of the yarn can be estimated, and the compactness between the monofilaments, namely, the clustering property of a yarn, can be calculated. As shown in Figure 9, a convex polygon including all monofilaments is drawn on the synthetic laser image of C1200 glass yarn. The included angle of any two edges of the polygon inside the polygon is not more than 180°, which means that the polygon has no depression. The area of this convex polygon can be easily measured by Image-Pro Plus.
and the measured area can be regarded as the cross-sectional area of the yarn.

If the cross-sectional area of the monofilament is defined as $S_i$, the cross-sectional area of the yarn is defined as $S_y$, the clustering property of the yarn can be calculated by the ratio of the sum of $S_i$ and $S_y$, as shown in equation (8):

$$ CP = \frac{\sum_{i=1}^{n} S_i}{S_y} = \frac{\sum_{i=1}^{n} \pi \left( \frac{d_i}{2} \right)^2}{S_y} \times 100\% . \quad (8) $$

It should be noted that the sum of $S_i$ is not equal to the sum of the monofilament cross-sectional areas in the synthetic laser image. In synthetic laser images, the cross-sectional images of some monofilaments are not complete circles. For measuring the diameter, as long as the image of a monofilament cross section is larger than a semicircle, the monofilament diameter data can be accurately measured. However, for measuring the area, the $S_i$ calculated in equation (8) is more accurate. If the cross-sectional areas of all the filaments in the synthetic laser image are measured directly, the measured areas are less than the sum of $S_i$.

According to the calculation method of equation (8), the clustering property of C1200 yarn in Figure 9 is evaluated. The sum of $S_i$ is 1,974 $\mu m^2$, and $S_y$ is 9,046 $\mu m^2$ measured by Image-Pro Plus. Therefore, the clustering property of C1200 yarn is 21.8%. The clustering property of D900 and BC1500 yarns is also evaluated by the same calculation method, as shown in Figures 10 and 11.

The sum of $S_i$ of D900 yarn is 2,692 $\mu m^2$, the cross-sectional area $S_y$ in Figure 10 is 11,931 $\mu m^2$, and the clustering property of D900 yarn is 22.6%.

The sum of $S_i$ of BC1500 yarn is 1,733 $\mu m^2$, the cross-sectional area $S_y$ in Figure 11 is 6,105 $\mu m^2$, and the clustering property of BC1500 yarn is 28.4%. The clustering property of different types of yarns can be evaluated by the monofilament diameter measured by the synthetic laser image and the calculation method of equation (8), and the cross-sectional shape of the yarn can be roughly judged by the drawn polygon.

(2) In addition to measuring the monofilament diameters of glass yarns, this method can also be applied to other filament yarns with a high bending stiffness, such as carbon fiber (CF) yarns and basalt yarns as shown in Figure 12. However, laser confocal microscopes are required for this method. Therefore, its instrument requirements are higher than those of the traditional method.

(3) Continuous filament yarns with 50 or 100 monofilaments can be directly magnified 1,000 times for experiments. For continuous filament yarns with 200 or more monofilaments, it is necessary to use a lens with a larger field of vision, or to use an electric X–Y platform for automatic image stitching, so that all the monofilaments can be in the same field of vision.
In addition to measuring the monofilament diameters of high bending stiffness yarn, synthetic laser images of a yarn’s cross sections can also be used to observe the fiber stratification [21]. Researchers can obtain images of a yarn’s cross sections from a fabric sample. The fiber stratification of a yarn’s cross sections can be observed directly, and the spreading effect can be evaluated by comparing the changes in the number of fiber layers, as shown in Figure 13. For example, the weft of grey fabrics has 6–8 layers of fibers, the weft of spread fabrics can have as few as 3 layers of fibers, and high-quality spread fabrics have only 2 layers of fibers.

5 Conclusion

In this article, a simple method for measuring the monofilament diameter of high bending stiffness yarn is discussed. The method for sample preparation is convenient and efficient and does not involve slicing samples. In addition to measuring the average diameter, this method can be used to measure the diameters of most of the monofilaments of a single yarn quickly using one test. Also, the distribution of the diameters can be obtained. The result shows that the average difference in the monofilament diameters measured by the transverse section method and the synthetic laser imaging method is less than 2%. Several problems associated with traditional methods will also not be encountered, such as the complex preparations necessary for slicing samples, difficult and costly operations, and the small amount of fiber diameter data ultimately obtained. The synthetic laser imaging method can help factories with prompt monitoring during production and to control the uniformity of the monofilament diameters through process adjustments. In addition, the yarn clustering property can be evaluated by the sum of the monofilament diameters and the yarn cross-sectional area.

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