Research Article

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Influence of technical parameters on the structure of annular axis braided preforms

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Abstract: A modified vertical braiding machine and closed annular axis mandrels with a special-shaped cross section were used to braid annular axis preforms under four different technical parameters. After measuring the braiding angles and yarn spacing of the braided preform in different areas of the mandrels, it was found that the braiding angle increased by 20.9% and the yarn spacing decreased by 19.8% when the speed of the yarn carrier was doubled. The braiding angle decreased by 31.1% and the yarn spacing increased by 28.6% when the rotation speed of the mandrels was doubled. The results show that the rotation speed of the mandrel has a slightly greater influence on the braiding angle and the yarn spacing. By using the modified braiding machine to braid the annular axis preforms, multi-layer continuous braided preforms can be achieved on compact equipment. And the structure of the annular axis braided preforms can be changed by changing the technical parameters.

Keywords: braiding, mandrel, braiding angle, yarn spacing, cross section

1 Introduction

Vertical braiding machine is a kind of ordinary two-dimensional (2D) braiding machine. Two groups of yarn carriers drive the yarns to interlace on the mandrel and form a braid. One end of the braided yarn is driven by a yarn carrier installed on the track plate, and the other end is braided on the mandrel. The mandrel usually moves in a straight line by a traction device [1]. Braiding angle and yarn spacing are the main parameters of braided preform structure [2].

Two-dimensional braiding theory has been a hot topic in recent years, especially in braided composite preform research. Zhang et al. analyzed 2D braid geometry and found that the cover factor of a fabric braided on a particular braider depends on three variables [3]. Kessels and Akkerman presented a model to predict the braiding angle on complex non-axisymmetric braided preforms [4]. Rawal et al. dealt with the simulation of various braided structures [5]. Birkefeld et al. characterized fiber architecture of biaxial and triaxial carbon fiber braids with off-axis braiding angles of 30°, 45°, and 55° [6]. Guyader et al. focused on the modeling of a 2D and three-dimensional (3D) circular braiding process based on differential geometry [7]. Gao et al. presented a 2D braiding design system for advanced textile structural composites based on dynamic models [8]. Na et al. developed a mathematical model to predict the braid pattern by braiding process on arbitrary-shaped mandrels considering braiding process parameters [9]. Ravenhorst and Akkerman designed an inverse kinematics-based procedure and generated numerical control data for a complex mandrel with a specified braid angle and a triaxial braid [10]. Fouladi et al. presented a method for controlling the braid angle on every side of a flat mandrel with the help of an elliptical guide ring to be added to the braiding machine [11]. Hajrasouliha et al. presented a theoretical model for the prediction of braid angle at any point of a mandrel with constant arbitrary cross section by taking into account the kinematic parameters of circular braiding machine [12].

Most braided parts usually move in a straight line on an ordinary braiding machine [13], and most mandrels are linear. For multi-layer composite preforms, it needs to take up forward and backward to have more than one layer. This conventional method causes a lot of waste and brings difficulties in stabilizing each layer in later manufacturing steps. This article presents a modified braiding machine that is able to braid yarns onto annular 3D shape continuously. The mandrel of the modified braiding machine is not required to go back and forth to achieve

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the required thickness and coverage, whereas preforms can be built in one go by continuously advancing the mandrel, so that all yarns are braided on the mandrel continuously without any termination, which can also minimize waste. The closed annular axis preforms such as bicycle rims can be achieved by the modified braiding machine. Four different technical parameters were used to braid preforms on closed annular axis mandrels with a special-shaped section. Then, the braiding angles and yarn spacing of braided preforms in different areas of the mandrels were measured to study the influence of technical parameters on the structure of the annular axis braided preforms with special-shaped sections.

2 Equipment

Ordinary braiding machines cannot directly use the closed annular axis mandrels for braiding. Therefore, a modification scheme for the ordinary vertical braiding machine was designed. The braiding machine is composed of a retractable track plate and an annular axis mandrel driving device, with a short yarn carrier and a retractable braiding ring, as shown in Figure 1. The retractable track plate enables the closed annular axis mandrel to move freely through the braiding area of the machine. The driving device of the annular axis mandrel is in the form of spokes connecting the roller, which transfers the rotation of the roller to the annular axis mandrel, enabling the mandrel to rotate around its own center. The short yarn carrier [14] ensures that the closed annular axis mandrel does not affect the movement of the yarn carrier. The traditional braiding direction is changed by the retractable braiding ring and the mandrel driving device can move the mandrel under the track plate, which not only ensures that the braiding convergence area is perpendicular to the track plate but also solves the space limitation problem caused by the limited diameter of the braiding machine track plate and the annular axis mandrel.

A notched rack, a fixed plate, a movable plate, a guide rail, and a stop block are included in the retractable track plate. The fixed plate and the movable plate are installed on the rack, and their combination forms the same eight-shaped track as in the ordinary vertical braiding machine. The dials and yarn carriers are placed on the track, and a slot in the center of the track plate allows the mandrel to pass through. The notched rack refers to the rack where the track plate is placed. There is a gap on one side of the upper layer of the rack, which ensures that the mandrel can easily pass through. The main motor is connected to the dial through a geared transmission to drive the yarn carrier to move back and forth on the eight-shaped track. The movable plate moves along the guide rail, and the intersection of the movable plate and the fixed plate corresponded to the gap of the rack. When the mandrel moves in or out, the main motor stops working and the movable plate is pulled outward along the guide rail to the stop block. After the mandrel moves in or out, the movable plate is pushed back to its original position along the guide rail and connected with the fixed plate.

The annular axis mandrel is held and driven by the annular axis mandrel driving device with connected spokes and a grooved roller. One end of the spoke is installed on a height-adjustable bracket. The top of the bracket is connected to an axis perpendicular to it and is connected to three spokes. The position of the spokes can be adjusted with the axis of the bracket as the center, and the length of the spokes can be adjusted to adapt to the annular mandrel with different diameters, which facilitates the loading and unloading of the closed annular axis mandrel. The other end of the spoke is connected to a grooved roller through a roller frame, and the mandrel is sheathed in the groove of the roller to ensure stability during the mandrel's rotation.

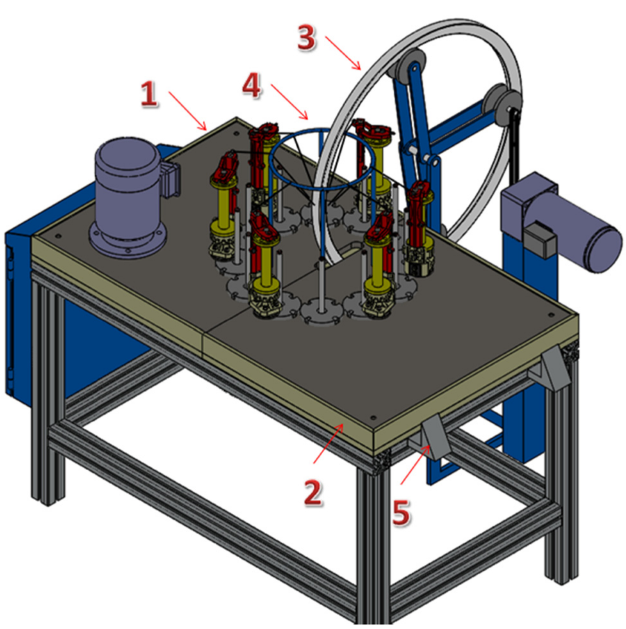

Figure 1: Schematic diagram of the annular axis braiding machine (1: fixed plate, 2: movable plate, 3: mandrel, 4: braiding ring, and 5: stop block).

The retractable braiding ring is supported by the braiding ring bracket, which is divided into two retractable parts. One part is installed on the fixed track plate and the other part on the movable plate, which can move synchronously with the movable plate. When the track plate is closed, the braiding ring is connected as a whole. The braid yarn passes through the braiding ring from the outside to the top and then moves down to form a braid on the surface of the mandrel. By adjusting the height of the mandrel driving device bracket, the braiding ring and the mandrel center can be on the same horizontal line. In this way, the convergence area of the yarn is not only in the center of the braiding machine track plate but also on the horizontal line of the center of the annular axis mandrel. Furthermore, it is also perpendicular to the track plate. Therefore, the eccentricity or non-vertical braiding direction caused by the annular movement of the annular axis mandrel can be avoided [2].

Before commencing the braiding, the annular axis mandrel is sheathed on the mandrel driving device, and the movable plate is pushed outward along the guide rail to the stop block, to separate from the fixed plate. Meanwhile, the braiding ring is opened too. Next, the mandrel driving device moves to push the mandrel into the convergence area at the center gap of the braiding machine track plate, and the movable plate is pushed back to the original position along the guide rail to connect with the fixed plate, to form a whole. The braid yarn is drawn out from the yarn carrier. The yarn passes through the braiding ring from the outside to the top, and then moves downward, concentrating toward the mandrel direction. The yarn is bound to the surface of the mandrel and starts braiding. The preform is drawn by the mandrel driving device to move under the track plate, as shown in Figure 2. After the braiding of the preform, the movable plate repeats the above action to separate from the fixed plate, and the braided preform and mandrel are taken out from the mandrel driving device.

By using the modified braiding machine, the problem of the ordinary braiding machine being able to only braid on a linear mandrel but not on a closed annular axis mandrel is solved. Furthermore, multi-layer continuous braided preforms can be achieved on compact equipment. The annular axis preform is braided in one go by continuously advancing the mandrel, and all yarns are braided on the mandrel continuously without any termination.

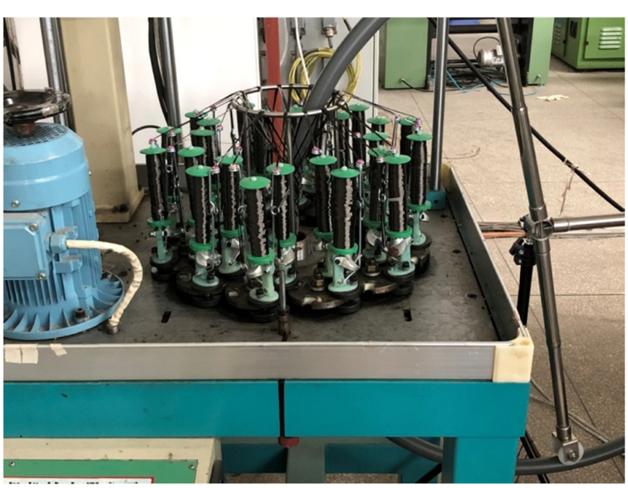

Figure 2: Actual image of the annular axis braiding machine.

3 Experiment

3.1 Mandrel

The cross section of the mandrel used in the experiment is not circular or any other regular shape but is designed as a combination of a curve and a straight line, as shown in Figure 3. The angle between the two intersection points of the curve and the straight line and the angle at the bottom of the curve are large. The presence of a big turning point when the yarn is braided at these three points is foreseeable.

Three turning points of the mandrel were used to divide the profile of the mandrel into three different areas of a continuous surface. The radius of the whole closed annular axis mandrel is 255 mm; the actual mandrel is shown in Figure 4. The material used for the mandrel is polypropylene.

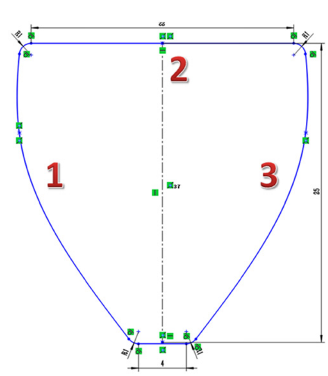

Figure 3: Schematic diagram of cross section of the mandrel.

Figure 4: Actual image of the annular axis mandrel.

3.2 Technical parameters

Two yarn carrier speeds and two mandrel rotation speeds were used in the modified 24-spindle vertical braiding machine during the braiding process. The experiment was divided into four groups, and the technical parameters for each group are shown in Table 1.

3.3 Braiding

The braid yarn used in the experiment is T700-12K carbon fiber yarn with a density of 1,800 kg/m^3, an elastic modulus of 230 GPa, and Poisson's ratio of 0.307. According to the technical parameters in Table 1, four groups of samples were braided in turn. The actual image of the braided preform using the second group of technical parameters is shown in Figure 5.

3.4 Braiding angle measurement

Due to the special-shaped cross section mandrel, the mandrel radius is not uniform at different positions of

Table 1: Technical parameter settings for each group

Experimental group no.	Yarn carrier speed (rpm)	Mandrel rotation speed (rpm)
1	70	5
2	70	2.5
3	35	5
4	35	2.5

Figure 5: Actual image of the braided preform.

the mandrel, and a fixed value cannot be used to characterize the braiding angle [15]. Therefore, it is necessary to measure the braiding angles at different positions of the mandrel separately.

As shown in Figure 3, three turning points of the mandrel were used to divide the profile of the mandrel into three different areas of a continuous surface, which were then photographed. The braiding angles were measured by image processing software after the preform photos of different areas were obtained. The image analysis software Image-Pro Plus was used and data on the intersecting angles of the two pairs of yarns were obtained using the angle measurement function of the software's measurement tool, as shown in Figure 6.

3.5 Yarn spacing measurement

Similar to the measurement of the braiding angles, the yarn spacing was measured by Image-Pro Plus through

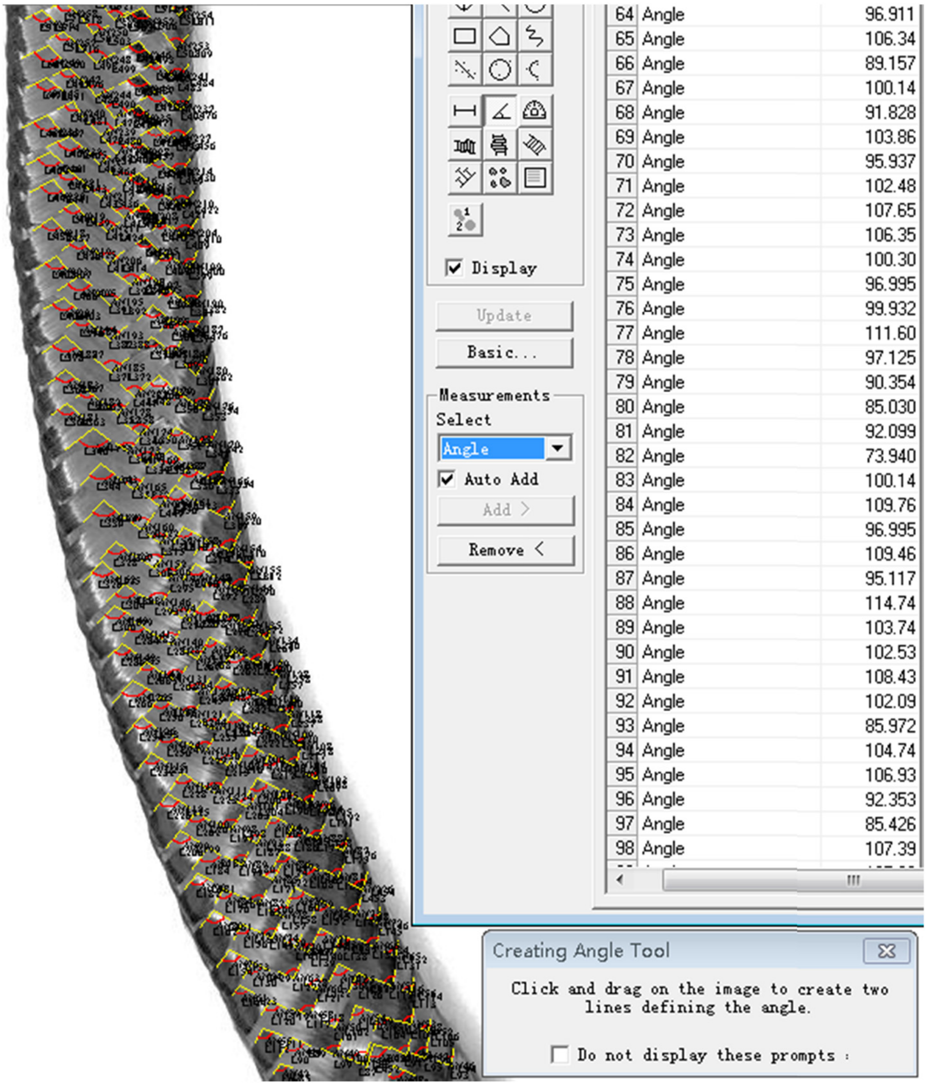

Figure 6: Measurement of braiding angles.

the distance measurement function in the measurement tool. To increase the yarn spacing measurement accuracy, the measurement tool "distance from a line" was taken for multi-point measurement, as shown in Figure 7.

The specific method of multi-point measurement is to select the center line of a yarn as the reference line and select three points on each of the two adjacent yarns. These three points are also on the center line of the yarn. The average value of the normal distance between the three points and the reference line is the distance between the yarn and the reference yarn. The schematic diagram of yarn spacing measurement according to this method is shown in Figure 8. The yarn spacing of two group yarns in both directions should be measured.

The mark display colors and the annotations were set in the test options, to clearly indicate the yarn spacing

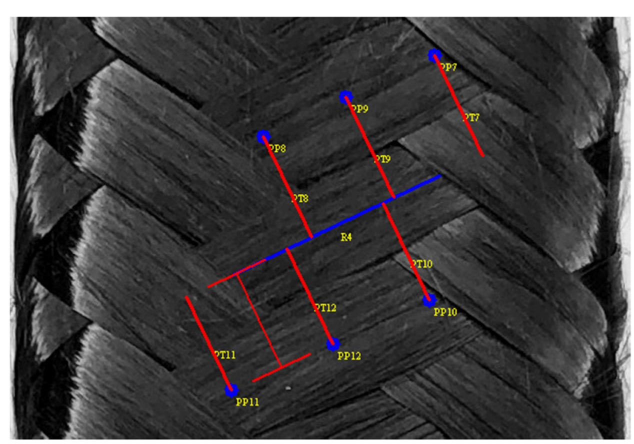

Figure 7: Schematic diagram of multi-point measurement method of yarn spacing.

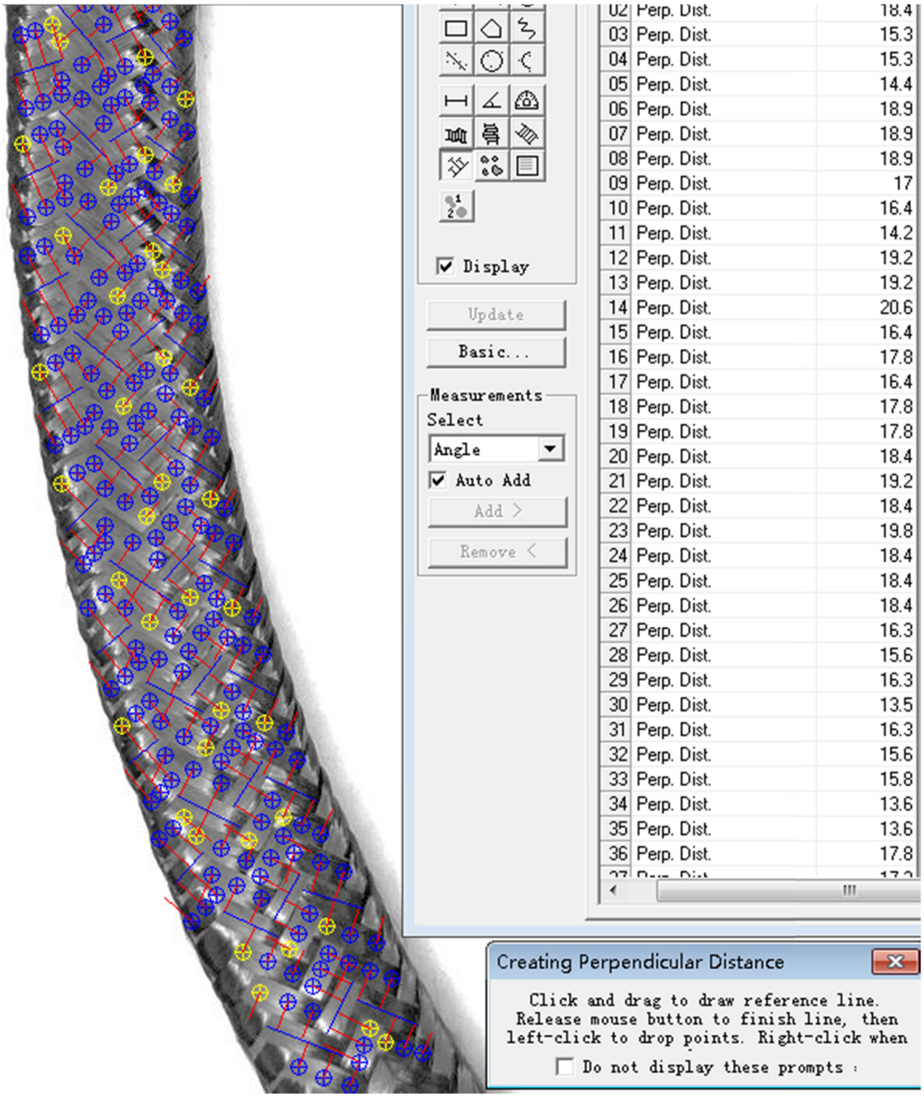

Figure 8: Measurement of yarn spacing.

and to ensure accurate measurements. The data of yarn spacing could be more accurate due to the multi-point measurement method.

4 Results

4.1 Braiding angles

The angles between two yarns of different braiding directions were measured. One half of each angle is taken as the braiding angle of the four groups of experimental samples. And the statistical data of braiding angles were obtained, as shown in Table 2.

According to the statistical data of the braiding angles in Table 2 and the experimental grouping in Table 1, it can be seen that at constant speed of the yarn carrier, the braiding angles decrease with an increase in the rotation speed of the mandrel. When the mandrel rotation speed

Table 2: Statistical data of braiding angles

Experimental group no.	Area 1 (°)	Area 2 (°)	Area 3 (°)	Average (°)
1	35.1	37.9	35.8	36.3
2	50	53.4	50.2	51.2
3	27.5	28.7	27.4	27.9
4	40.1	43.1	41.9	41.7
Average	38.2	40.8	38.8	39.3

is doubled, the braiding angles decrease by an average of 31.1%. When the rotation speed of the mandrel is constant, the braiding angles increase with an increase in the speed of the yarn carrier. When the speed of the yarn carrier is doubled, the braiding angles increase by an average of 20.9%.

More specifically, when the mandrel rotation speed remains unchanged, the influence of the yarn carrier speed on the braiding angles is 23.1 and 18.6%, respectively. When the speed of the yarn carrier remains unchanged, the influence of the mandrel rotation speed on the braiding angles is 29.1 and 33.1%, respectively, which shows that the rotation speed of the mandrel has a slightly greater influence on the braiding angles.

It can also be found from Table 2 that when the speed of the yarn carrier is the highest and the rotation speed of the mandrel is the lowest, the braiding angle is the largest. When the speed of the yarn carrier is the lowest and the rotation speed of the mandrel is highest, the braiding angle is the smallest. The difference between the maximum and minimum braiding angles reached 45.5%.

In addition, comparing the braiding angles in different areas of the same group of samples revealed that the braiding angle of area 2 is the largest, the braiding angles of area 1 and area 3 are smaller, and the average braiding angle of area 2 is 5.6% larger than that of area 1 and area 3.

4.2 Yarn spacing

The yarn spacing in different areas of the four groups of experimental samples was measured in turn by the aforementioned multi-point measurement method, and the statistical data of yarn spacing were obtained, as shown in Table 3. It should be noted that the original data measured are the pixel data on the picture, so it is necessary to convert it into the actual yarn spacing data according to the magnification of the picture.

From the statistical data of yarn spacing in Table 3 and the experimental grouping in Table 1, it can be seen that when the speed of the carrier is constant, the yarn spacing increases with an increase in the rotation speed of the mandrel. When the mandrel rotation speed is doubled, the yarn spacing increases by an average of 28.6%. When the rotation speed of the mandrel is constant, the yarn spacing decreases with an increase in the speed of the yarn carrier. When the speed of the yarn carrier is doubled, the yarn spacing decreases by an average of 19.8%.

Table 3: Statistical data of yarn spacing

Experimental group no.	Area 1 (mm)	Area 2 (mm)	Area 3 (mm)	Average (mm)
1	6.4	6.7	6.1	6.4
2	4.5	5.5	4.5	4.8
3	8.6	9.5	7.3	8.4
4	5.1	7.0	4.8	5.7
Average	6.1	7.2	5.7	6.3

Specifically, when the rotation speed of the mandrel remains unchanged, the influence of the speed of the yarn carrier on the yarn spacing is 23.8 and 15.8%, respectively. When the speed of the yarn carrier remains unchanged, the influence of the mandrel rotation speed on the yarn spacing is 25.0 and 32.1%, respectively, which shows that the mandrel rotation speed has a slightly greater influence on the yarn spacing.

It can also be found in Table 3 that when the speed of the yarn carrier is the lowest and the mandrel rotation speed is the highest, the yarn spacing is the largest. When the speed of the yarn carrier is the highest and the mandrel rotation speed is the lowest, the yarn spacing is the smallest. The difference between the maximum and minimum yarn spacing reached 42.9%.

In addition, comparing the yarn spacing in different areas of the same group of samples revealed that the yarn spacing in area 2 is the largest, while the yarn spacing in area 1 and area 3 is smaller, and the average yarn spacing in area 2 is 18.1% larger than that in area 1 and area 3.

5 Discussion

5.1 Significance of annular axis braiding

By using the modified vertical braiding machine to braid the annular axis preform, multi-layer continuous braided parts can be achieved on compact equipment. The linear braiding parts can be braided on a linear mandrel by using an ordinary braiding machine, and then it can be bent into annular axis braiding parts. However, it is discontinuous and difficult to obtain multi-layer braiding parts in this way. Moreover, bending linear braiding parts with external force may cause slippage and friction of yarn on the mandrel [16], and the result is not the same as braiding directly on the annular axis mandrel. The advantage of the present structure is that the braid yarns are continuous in the braided parts. All the yarns are directly formed into the annular axis braided structure in a single process, without disconnection or joint. In addition, it is possible to braid multiple layers in one go, and each layer is relatively stable between each other.

5.2 Difference of braiding angles in different areas of the mandrel

From the measurement results of the braiding angles, it is clear that there are some differences in braiding angles in the three areas of the mandrel, which are first related to the cross section shape of the mandrel. As the cross section of the mandrel has a special shape, the radius of the mandrel is not uniform in different positions of the mandrel. Hence, the braiding angle is also different. In addition, the difference in the braiding angles may be related to the change in the convergence area. In the process of annular axis braiding, the fluctuation of yarn tension leads to a change in the convergence area [17], due to which the braiding point of yarn falling on the mandrel and the center of the annular mandrel are not always on the same horizontal line and also deviate from the center point of the track plate of the braiding machine. In this way, there is a difference between the actual mandrel radius and the theoretical mandrel radius, further increasing the difference in braiding angles.

5.3 About the following processing steps

The mandrel is not removed immediately after braiding, but after the resin is cured to the preform. Holes need to be drilled on the material after resin curing, and the melting point of the mandrel material is not high, so the mandrel will melt and flow out of the holes at high temperature. After the mandrel is removed, the annular axis braided composite with similar shape to the closed ring mandrel can be obtained. However, it is almost impossible to get a similar braided composite on an ordinary braiding machine by using a common method such as braided rope [13], or by using a linear mandrel braiding.

6 Conclusion

In this article, the influence of technical parameters on the structure of annular axis braided preforms using special-shaped cross section was studied. The results show that when the speed of the yarn carrier is doubled, the braiding angle increases by 20.9%, and the yarn spacing decreases by 19.8%. When the mandrel rotation speed is doubled, the braiding angle is decreased by 31.1%, and the yarn spacing is increased by 28.6%. The rotation speed of the mandrel has a greater influence on the braiding angles and the yarn spacing. By studying the braided preform structure under different technical parameters, the annular axis braiding rules with a special-shaped cross section can be further comprehended. So the structure of braided preforms can be changed based on actual needs, and a foundation for the study of the composite reinforcement properties of its braided preforms has also been laid.

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