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Production of Carbon Fibre Bulked Yarns by the Airflow Dispersion Method

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Abstract
Using carbon fibre tows as raw materials, carbon fibre bulk yarns were produced by the airflow dispersion method for the first time. The breaking strength, strength irregularity, yarn irregularity and hairiness index of the carbon fibre bulk yarn were used as evaluation indices, and preparation technology for carbon fibre bulk yarn was optimized using the orthogonal experimental method. Subsequently the disordered structure of homemade carbon fibre bulk yarn, the ability to fix the resin, and the surface contact angle were investigated. Finally infrared spectral analysis of the carbon fibre bulk yarn was carried out. Results show that the best preparation technology for carbon fibre bulk yarn is as follows: nozzle air pressure 0.45 Mpa, spinning speed 150 m/min, and nozzle diameter 2.2 mm. The degree of disorder of fibres of T700 carbon fibre bulk yarn fibre is 18.70%~25.60%; as the degree of disorder of carbon fibre bulk yarn increases, the ability to fix the resin is enhanced. The process of carbon fibre tows producing bulk yarns is a physical one.

Key words: *carbon fibre, bulk yarn, development, properties.*

Introduction

Bulk yarn is a new type of structure of yarn produced by the air injection method. When continuous fibre yarn passes through the bulk deformation nozzle, it experiences the shocks and disturbances of turbulent flow formed by the compressed air in the nozzle, which leads to the fibres in the yarn separating. Then the volume increases, and bulk yarn is formed [1-5]. Due to the processing characteristics used, bulk yarn has the advantages of continuous fibres and fixed length fibres, such as bulk, good handle, high coverage, and the yarn strength and evenness are both higher than for fixed length fibre [6-7]. Bulk yarns have the following characteristics: 1) the imitation of staple fibre yarns, namely that their surface layer has similar geometric characteristics to staple fibre yarns, while the aurora properties and waxy feeling of the yarn are effectively improved; 2) bulkiness, which refers to the volume of original fibre tows increasing by 50% ~ 150% after air deformation processing, which can improve the wearability of the yarn and resulting fabrics. Special fibre bulk yarns are currently mainly based on fibreglass, but glass fibres are inferior to carbon fibres in terms of the properties of strength and resistance to high temperatures [7-9]. At present, bulk yarn products have extensive application in the United States, Germany, Japan and China [10-18]. Carbon fibre is produced from organic polyacrylonitrile fibre, viscose fibre, pitch fibre and other raw materials through a high temperature solid phase reaction process involving spinning, stretching, oxidation, carbonisation, graphitisation and other processes. Carbon fibres have the properties of high specific strength, high specific modulus, high temperature resistance, corrosion resistance, resistance to fatigue, creep resistance and a series of other excellent properties [19-22]. In addition, because the mass of carbon fibre and fabrics derived therefrom are light, they can be broken, bent and adapt to different component shapes. Molding is convenient, and they can also construct several layers in accordance with the needs of the bearing force, During construction, there is no need for large equipment, and there is no damage to the original structure [23-26]. In recent years, carbon fibre products have experienced great progress in terms of the technology, processing and other various aspects. The application fields have expanded, such as in civil engineering, transportation, pressure vessels, oil drilling and textile machinery, where their use has increased greatly [27-28].

In this article, using carbon fibre tows as raw materials, and deformation technology, carbon fibre bulked yarns were produced by the airflow dispersion method by this research group for the first time. The breaking strength, strength irregularity, yarn irregularity and hairiness index of the carbon fibre bulk yarn were used as evaluation indices, and preparation technology for carbon fibre bulk yarn was optimised using an orthogonal experimental method. Subsequently the disordered structure of the homemade carbon fibre bulk yarn, the ability to fix the resin, and the surface contact angle were investigated.

Experimental

Materials

T700 (12 k) carbon fibre tows, provided by the Japan Toray Company.

Instrumentation

PC-PH-IIglass fibre bulk yarn machine (Hangzhou Xiaoshan Tiancheng Machinery Co., Ltd.), Tensor37 Fourier transform infrared spectrometer (German BRUKER Company), YG004E single fibre electronic tensile strength tester (TiangxiangFang Equipment Co., Ltd.), YG172 hairiness tester (Shaanxi Changling Textile Mechanical And Electrical Technology Co., Ltd.), YG136A yarn uniformity testing analyzer (Shaanxi Changling Textile Mechanical And Electrical Technology Co., Ltd.), DCAT21 contact angle tester (Germany Data physics Company), etc.

Preparation of carbon fibre bulk yarn

Carbon fibre bulk yarns were produced by the airflow dispersion method by this research group for the first time using a PC-PH-IIglass fibre bulk yarn machine [29-30]. The airflow dispersion method for continuous function fibre bundles is a non-contact physical dispersion technique. The high speed air flow through the nozzle of the puffing machine blows and sprays continuously to produce continuous carbon fibre bulk silk, (referred to as bulk yarn) based on the single fibre dispersed state. The puffing process is shown in ***Figure 1***.

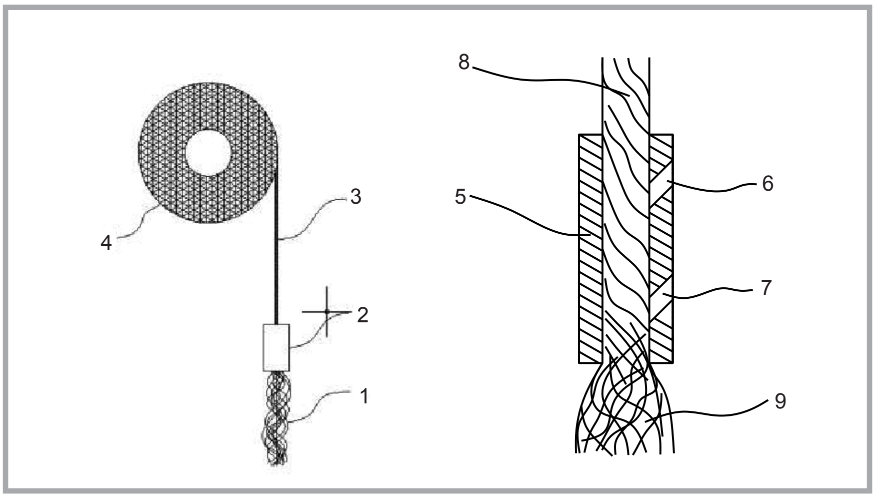

Figure 1. *Process schematic of yarn bulking: 1 – bulk yarn, 2 – high speed air flow of puffing machine, 3 – continuous function fibre bundle, 4 – endless fibre tow tube, 5 – puffing machine shape, 6 & 7 – guide holes, 8 – continuous function fibre bundle, 9 – bulk yarn.*

The carbon fibre bulk yarn is processed and formed on a filament extrusion machine, whose key component is the air nozzle. The technological process involves importing compressed air into the nozzle, where the tow experiences the effect of the high-speed turbulent flow inside the nozzle. Each root of the single fibres is separated from each other, and they move intensely with the turbulent flow. When the single fibres emerge from the nozzle under the condition of overfeeding, a large amount of entangled structures are formed by loose endless fibre bundles, and many silk rings and silk arcs are also formed [31-32]. This inordinate entanglement state leads to smooth and straight endless bundles becoming bouffant carbon fibre bulk yarn, as shown in ***Figure 2***.

Testing indices and methods

Yarn uniformity test

The yarn uniformity of carbon fibre bulk yarns was tested using a YG136A yarn uniformity testing analyser and the photo-electric method.

Mechanical properties test

The mechanical properties were tested using a YG004E single fibre electronic tensile strength tester in accordance with GB/T 7690.3 2001 for the breaking strength and breaking elongation of fibres.

Hairiness index test

The hairiness state of carbon fibre bulk yarn was tested and analysed using a YG172 hairiness tester.

Hairiness is an important quality index, affecting the appearance and style of the yarn. The state of yarn hairiness directly affects the weaving efficiency, cloth cover style, dyeing effect, etc. If the overall value of hairiness is larger, it will lead to the knitting cloth being unclear and will have a serious influence on the dyeing effect. If the value of hairiness irregularity is larger, the cloth is not level, which affects the dyeing performance; a few yarns have thick hairiness, which leads to the formation of cotton balls in the knitting channel, and the neps affect broken ends and the cloth cover quality.

Disorder structure test

The degree of disorder of carbon fibre bulk yarn was characterised using the method known as the intensity method, proposed by Dr Jiang Yan. The degree of disorder has a close relationship with the yarn mechanical anisotropy. Accordingly the breaking strength of carbon fibre bulk yarn and its original tows can be tested indirectly. The percentage loss of the strength for carbon fibre bulk yarn was calculated to calibrate the degree of disorder, for which ***Equation (1)*** can be used.

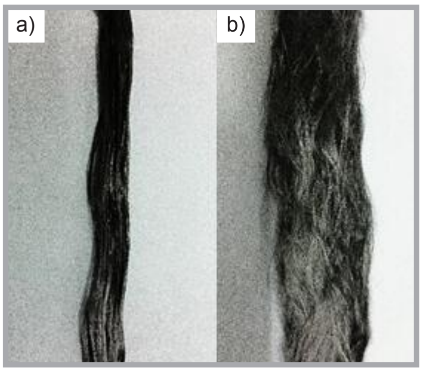

Figure 2. *Carbon fibre bulk yarns and carbon fibre tows without puffing: a) carbon fibre tows, b) carbon fibre bulk yarns.*

$$W = \frac{p_0 - p}{p_0} \times 100\% \qquad (1)$$

Where, W is the degree of disorder of the bulk yarn, p_0 the breaking strength of the tows (N), and p is the breaking strength of the bulk yarn (N).

Ability to fix the resin test

For the test of the ability to fix the resin for carbon fibre bulk yarn, a method involving calculating the difference between the weight of carbon fibre bulk yarn before and after combination with resin was used. In this experiment, the resin used was a heat-curing epoxy type, where the mass ratio of the epoxy resin components E54, AG80 and DDS was 2:3:2.

__Table 1.__ Experimental factor level table.

Factor levels	Spinning speed/m/min	Nozzle air pressure, MPa	Nozzle diameter, mm
1	140	0.4	2.2
2	150	0.45	2.5
3	160	0.5	2.8

__Table 2.__ Orthogonal test. __Note:__ A – spinning speed, B – nozzle air pressure, C – nozzle diameter.

	Scheme number	A	B	C	Hairiness index, root/meter	Yarn irregularity, %	Breaking strength, N	Strength irregularity, %	Elongation at break, %
	1	1	1	1	10.75	26.46	252.17	11.68	9.14
	2	1	2	2	12.73	27.73	247.12	14.36	10.65
	3	1	3	3	14.03	22.92	238.61	13.25	12.30
	4	2	1	3	12.12	29.11	258.24	12.21	10.87
	5	2	2	1	12.48	22.57	249.83	13.84	12.93
	6	2	3	2	14.07	23.24	251.03	11.37	13.40
	7	3	1	2	11.92	21.65	260.74	10.79	9.61
	8	3	2	3	12.81	22.60	258.73	10.59	12.74
	9	3	3	1	15.01	23.61	240.50	10.01	13.80
Hairiness index	K_1	35.51	34.79	38.24					
	K_2	38.67	38.02	38.72					
	K_3	39.74	43.11	38.96					
	Range	4.23	8.32	0.72					
Yarn irregu-larity	K_1	77.11	77.22	72.64					
	K_2	74.92	72.9	72.62					
	K_3	67.86	69.77	74.63					
	Range	9.25	7.45	2.01					
Tensile strength	K_1	737.9	771.15	742.5					
	K_2	759.1	755. 68	742.5					
	K_3	759.97	730.14	755.58					
	Range	22.07	41.01	13.08					
Strength irregularity	K_1	39.29	34.68	39.32					
	K_2	37.42	38.79	36.52					
	K_3	31.39	34.63	35.91					
	Range	7.9	4.16	3. 41					
Elongation at break	K_1	32.09	29.62	35.87					
	K_2	37.2	36.32	33.66					
	K_3	36.15	39.5	35.91					
	Range	5.11	9.88	2.25					

FTIR test

The infrared spectrum of the carbon fibre bulk yarn was obtained using a Tensor37 Fourier transform infrared spectrophotometer.

Surface contact angle test

The contact angle θ is the advance angle after the fibre and epoxy resin prepared come into contact with each other. The surface contact angle of fibres was measured using a DCAT21 contact angle tester.

Test conditions: increasing rate of platform – 0.05 mm/s, immersion rate of fibres – 0.01 mm/s, detection limit – 0.15 mg, and insertion depth – 3 mm.

In this experiment, the system of heat-curing epoxy resin was adopted, with the specific steps in preparing the resin as follows: First of all, the E54, AG80 and DDS were weighed at a mass ratio of 2:3:2. Then the E54 and AG80 were poured into a beaker together, and then stirred magnetically. The heating temperature was set to 120 °C on the heating device. Finally after the E54 was mixed evenly with AG80, DDS was slowly added, and stirred at 120 °C for about 1 hour, until the resin system was uniform and transparent visually.

Results and discussion

Mulberry fibers after bacteria degumming

Fineness and length of mulberry fibers

Figure 1 shows the dimension of mulberry fibers in the process of bacteria degumming. As seen from ***Figure 1***, an increase in the degumming time decreased the fineness of mulberry fibers but caused a reduction in the fiber length as well. When the time increased from 42 h to 48 h, fiber fineness decreased from 20.2 to 5.2 dtex, but the fiber length decreased drastically from 38 to 17 mm. Further prolonging the time would aggravate the reduction in the fiber length until the bark of otton/flax fabric. Softer and smoother hand could be attributed to the lower Young's modulus of mulberry fibers and more perfect yarn structure of blended yarns from mulberry fibers.

Orthogonal experimental investigation of the spinning process for carbon fibre bulk yarn

In this experimental investigation, three parameters: the spinning speed, nozzle air pressure and nozzle diameter ,were selected as the factors. Experimental factor levels are shown in ***Table 1***, and the experimental analysis and results are in ***Table 2***.

Intuitive analysis

In accordance with the range used, the primary and secondary order of importance of the three factors influencing five indices are arranged as follows: the breaking strength B > A > C, the strength irregularity A > B > C, the yarn irregularity A > B > C, and the hairiness index B > A > C. It can be seen from the ***Table 2*** that the differences in the influence of various factors on the breaking strength are obvious. The difference in the range value for the three factors: A, B and C is large; the influence of the three factors on the hairiness index is also obvious, while that of factor C on the hairiness index is very small, and that of factors A and B on the breaking strength and yarn irregularity is smaller relative to their influence on the breaking strength. Thus, based on overall consideration, the primary and secondary importance of the three factors is ordered as B > A > C.

On the basis of k_{1j},k_{2j},k_{3j}, the best combination of factor levels are determined as follows: the breaking strength $A_3B_2C_1$, strength irregularity $A_2B_2C_1$, yarn irregularity $A_2B_1C_1$, elongation at break $A_1B_1C_1$, hairiness index $A_1B_1C_1$.

Because the spinning process parameters are optimised mainly aimed at the breaking strength, the strength irregularity and yarn irregularity of spun yarns, it is concluded that the optimal parameter is $A_2B_2C_1$ after the overall balancing.

In order to further determine the significance of the influence of each factor on yarn quality, variance analysis of the experimental results was carried out.

The variance analysis

(1) Breaking strength

A variance analysis of the breaking strength was carried out, the results of which are shown in ***Table 3***.

As can be seen from the analysis above, for the breaking strength the influence of factor B (the nozzle air pressure) is the most significant, and that of factor A (the spinning speed) is relatively significant. Thus it is reasonable to consider only the values of A and B, and to take the value of C (the nozzle diameter) randomly; hence, the best process is A_2B_2C.

(2) Strength irregularity

A variance analysis of the strength irregularity was carried out, the results of which are shown in ***Table 4***.

As can be seen from the analysis above, for the strength irregularity, the influence of factor A (the spinning speed) is the most significant, and that of factor B (the nozzle air pressure) is relatively significant. Thus it is reasonable to consider only the values of A and B, and to take the value of C (the nozzle diameter) randomly; thus, the best process is A_2B_2C.

(3) Yarn irregularity

A variance analysis of the yarn irregularity was carried out, the results of which are shown in ***Table 5***.

As can be seen from the analysis above, for the yarn irregularity, the influence of factor C (the nozzle diameter) is the most significant. Thus it is reasonable to consider only the value of C, and that the best process is ABC_1.

(4) Hairiness index

A variance analysis of the hairiness index was carried out, the results of which are shown in ***Table 6***.

Table 3. *Breaking strength analysis of variance.*

Sources of variance	Bias squares S	Degrees of freedom f	Average of quadratic sums	F values	Significance	Critical values
A	104.142	2	52.071	2.080	–	–
B	285.937	2	129.4685	5.710	Significant	–
C	47.981	2	23.9905	0.958	–	–
e	50.08	2	25.04	–	–	–

Table 4. *Strength irregularity analysis of variance.*

Sources of variance	Bias squares S	Degrees of freedom f	Average of quadratic sums	F values	Significance	Critical values
A	11.363	2	5.6815	69.712	Significant	19
B	3.800	2	1.9	23.313	–	–
C	3.146	2	1.573	19.301	–	–
e	0.16	2	0.08	–	–	–

Table 5. *Yarn irregularity analysis of variance.*

Sources of variance	Bias squares S	Degrees of freedom f	Average of quadratic sums	F values	Significance	Critical values
A	15.578	2	7.789	17.523	–	–
B	9.329	2	4.6645	10.494	–	19
C	30.023	2	15.0115	33.772	Significant	–
e	0.89	2	–	–	–	–

Table 6. *Hairiness index analysis of variance.*

Sources of variance	Bias squares S	Degrees of freedom f	Average of quadratic sums	F values	Significance	Critical values
A	0.829	2	0.4145	9.211	–	19
B	11.729	2	5.8645	130.322	Significant	–
C	0.851	2	0.4255	9.456	–	–
e	0.09	2	0.045	–	–	–

Table 7. *Elongation at break analysis of variance.*

Sources of variance	Bias squares S	Degrees of freedom f	Average of quadratic sums	F values	Significance	Critical values
A	4.855	2	2.4275	4.394	–	–
B	16.957	2	8.4785	15.346	Significant	–
C	0.047	2	0.0235	0.043	–	9
e	1.10	2	0.55	–	–	–

Table 8. *Results of validation test.*

Indices	Experimental schemes				
	$A_1B_1C_1$	$A_3B_1C_2$	$A_3B_1C_3$	$A_3B_3C_1$	$A_2B_2C_1$
Yarn irregularity, %	26.11	21.46	23.01	23.73	21.24
Breaking strength, N	250.61	258.12	257.83	240.25	260.50
Maximum value of breaking strength, N	270	285	285	290	285
Minimum value of breaking strength, N	201	206	211	218	219
Strength irregularity,%	11.36	10.79	10.84	10.87	9.37
Elongation at break, %	9.14	10.01	13.40	12.87	12.93
Hairiness index, root/meter	10.73	11.91	15.12	14.07	12.48

Table 9. *Degree of disorder of each sample.*

Number	P, N	P_0, N	W, %
$A_1B_1C_1$	252.17	320.72	21.37
$A_1B_2C_2$	247.12	320.72	22.95
$A_1B_3C_3$	238.61	320.72	25.60
$A_2B_1C_3$	258.24	320.72	19.48
$A_2B_2C_1$	249.83	320.72	22.10
$A_2B_3C_2$	251.03	320.72	21.73
$A_3B_1C_2$	260.74	320.72	18.70
$A_3B_2C_3$	258.73	320.72	19.33
$A_3B_3C_1$	240.50	320.72	25.01

Table 10. *Ability to fix the resin of yarns.*

Number of the yarn	Weight of the yarn not combining with the resin, g	Weight of the yarn combining with the resin after drying, g	Weight of the fixed resin, g
$A_1B_3C_3$	0.1738	0.9907	0.8169
$A_3B_3C_1$	0.1724	0.9662	0.7938
$A_3B_2C_3$	0.1753	0.7290	0.5537
$A_3B_1C_2$	0.1771	0.8125	0.6354
The original fibre tows without puffing	0.1775	0.5329	0.3554

As can be seen from the analysis above, for the hairiness index, the influence of factor B (the nozzle air pressure) is the most significant, and hence it is reasonable to consider only the value of B, and that the best process is AB_1C.

(5) Elongation at break

A variance analysis of the elongation at break was carried out, the results of which are shown in ***Table 7***.

As can be seen from the analysis above, for the elongation at break, the influence of factor B (the nozzle air pressure) is the most significant, and hence it is reasonable to consider only the value of B; thus, the best process is AB_1C.

In this experimental investigation, the breaking strength and yarn irregularity of bulk yarns are the main targets for process optimisation. Thus the three important indicators of breaking strength, strength irregularity and yarn irregularity are considered primarily, and based on the analysis of the above, $A_2B_2C_1$ is selected as the optimal spinning process for carbon fibre bulk yarns.

To further verify the validity of the orthogonal experiment, four schemes for the minimum hairiness index, maximum breaking strength, minimum yarn irregularity and minimum strength irregularity were selected from the orthogonal experimental results given in ***Table 6*** (schemes 2, 6, 7 & 9, respectively). Spinning experiments were carried out combining the four schemes with the optimal process obtained from the orthogonal experiments, comparing the spinning properties. The experimental results are shown in ***Table 8***.

Table 8 shows that with $A_2B_2C_1$ (optimal process combination), as compared with $A_1B_1C_1$ and $A_3B_1C_2$, the hairiness index is larger, but the difference is very small. Also the breaking strength, strength irregularity and yarn irregularity are better than with the other schemes. Because the strength is the main index, and the hairiness of carbon fibre bulk yarns is high, $A_2B_2C_1$ represented the best structure parameters of the nozzle. When the nozzle air pressure is 0.45 Mpa, the nozzle diameter is 2.2 mm and the spinning speed 150 m/min; the spinning process is therefore the best.

Disordered structure of carbon fibre bulk yarn

The disordered structure features of carbon fibre bulk yarn can be characterised using the degree of disorder. It is difficult to measure the degree of disorder of fibre directly, but an approximate direct method and indirect method can be used to test it.

Table 9 shows that the degree of disorder of the fibre of T700 (12 k) carbon fibre bulk yarn is 18.70% ~ 25.60%. When the degree of disorder is the highest, the process parameters used for carbon fibre bulk yarn are as follows: spinning speed 140 m/min, nozzle air pressure 0.5 MPa, and nozzle diameter 2.8 mm. When a smaller spinning speed matches the strong airflow spray, the carbon fibre bundles are blown and sprayed fully. Spray in the turbulence in the nozzle leads to a disordered state of single fibre in the carbon fibre tows being formed. When the degree of disorder is the lowest, the spinning process used for bulk yarn is as follows: spinning speed 160 m/min, nozzle air pressure 0.4 MPa, and nozzle diameter 2.5 mm. Compared with the spinning process for carbon fibre bulk yarn where the degree of disorder is the highest, it can be seen that the faster spinning speed matches the smaller nozzle air pressure, which leads to the blowing and spraying effect of air in the nozzle not being strong enough.

From the analysis of the structure of carbon fibre bulk yarn above, it is shown that carbon fibre bulk yarn has the characteristics of high bulk and a disordered structure. The bulk and disorder properties provide a larger specific surface area compared to the original tows, which will change the ability of carbon fibre tows to fix the resin. Next in this article, the ability to fix the resin of carbon fibre bulk yarn was explored in accordance with the characteristics of carbon fibre bulk yarn.

Analysis of the ability of carbon fibre bulk yarn to fix the resin

For the test of the ability of carbon fibre bulk yarn to fix the resin, the method of calculating the difference in the weight of carbon fibre bulk yarn before and after combination with resin was used. In this experimental investigation, the resin used was the heat-curing epoxy type, and the mass ratio of the epoxy resin components E54, AG80, and DDS was 2:3:2. Five groups of experimental samples were selected, including $A_1B_3C_3$ and $A_3B_3C_1$, which were the samples with higher bulking intensity and a larger degree of disorder, $A_3B_1C_2$ and $A_3B_2C_3$, which were the samples with the relatively lower bulking intensity and degree of disorder, and the fifth sample was T700 carbon fibre original tows. Test results are shown in ***Table 10***.

It can be seen from ***Table 10*** that the ability to fix the resin of carbon fibre bulk

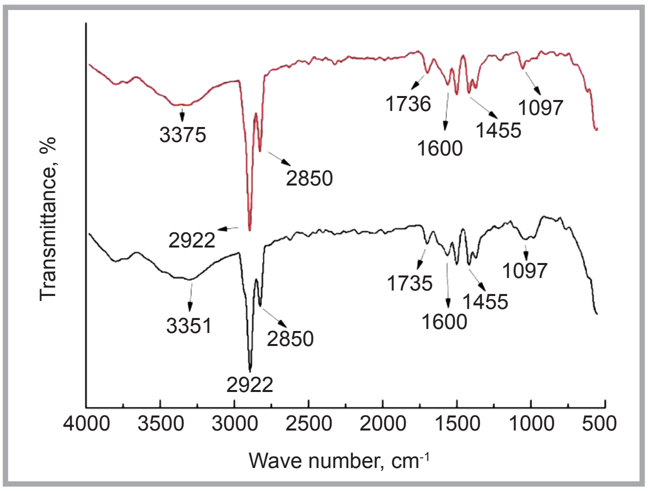

Figure 3. *Infrared spectrum of carbon fibre bulk yarn and carbon fibre original tows.*

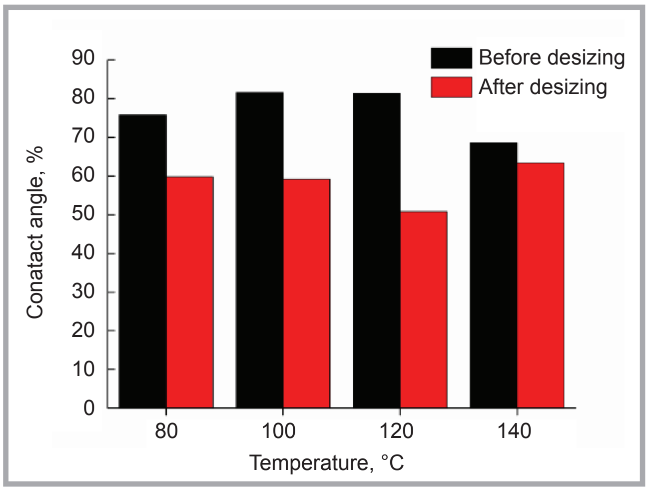

Figure 4. *Contact angle of carbon fibre bulk yarn.*

yarn is obviously stronger than that of carbon fibre original tows. Using the same mass, the average mass of carbon fibre bulk yarn fixing the resin is 0.6999 g, and the mass of carbon fibre original tows combining with the resin is 0.3554 g, the two differing by nearly a factor of two. The single fibres of carbon fibre bulk yarn are in a state of separation. The fibres in tows without puffing are closer, and thus the specific surface area of the carbon fibre bulk is larger than that of the carbon fibre tows without puffing. There are many gaps between the carbon fibre bulk yarns after the air spraying, but the surface of tows is flat and smooth without puffing. Due to the two factors above, for the properties of combining with the resin, bulk yarn is obviously better than tows without puffing. In the forming process of composite materials, using resin as the matrix and carbon fibre products as reinforced material, the more resin the reinforced material fixes, the stronger the integrity of the composite material relatively. Carbon fibre bulk yarn products can effectively increase the contact area of the resin and fabrics, which leads to the resin completely permeating the whole fabric, and eventually the whole composite is formed.

It can also be seen from ***Table 10*** that the ability of samples $A_1B_3C_3$ and $A_3B_3C_1$, with the higher bulking intensity and larger degree of disorder, to combine with the resin is significantly stronger than for samples $A_3B_1C_2$ and $A_3B_2C_3$, with relatively lower bulking intensity. The specific surface area of carbon fibre bulk yarn is larger with a higher bulking intensity. At the same time, the higher bulking intensity and degree of disorder also leads to more gaps in carbon fibre bulk yarn. Thus the ability of carbon fibre bulk yarn with the higher bulking intensity and larger degree of disorder to combine with the resin is also good.

Infrared spectral analysis of carbon fibre bulk yarn

Figure 3 shows that peaks at 3375 cm^{-1} and 3351 cm^{-1} may be unsaturated C-H stretching vibration absorptions (VCH); that at 2922 cm^{-1} is the antisymmetric stretching vibration absorption peak of methylene; that at 2850 cm^{-1} is the symmetric stretching absorption peak of methylene, those at 1736 cm^{-1} and 1735 cm^{-1} are the stretching vibration absorption of C = O; that at 1600 cm^{-1} is the arene skeleton vibration absorption peak; that at 1455 cm^{-1} is the deformation and vibration absorption peak of methyl or methylene, and that at 1097 cm^{-1} is the symmetric stretching vibration absorption peak of C-O-C. Based on the analysis above, it can be seen that the sizing agent on the surface of T700 carbon fibres contains groups interacting with epoxy resin. In general, the closer the polarity of the two substances, the lower the interfacial tension, the stronger the interaction, and the sizing agent can improve the interfacial bonding of fibres and epoxy resin. In addition, before and after spraying with air, the types of groups on the sizing agent and the peak strengths are almost unchanged, which illustrates that the air spraying process causes no changes in the chemical properties of carbon fibres; hence, the process of original carbon fibre tows producing bulk yarn is a physical one.

Contact angle analysis of fibres for carbon fibre bulk yarn

As can be seen from ***Figure 4***, at low temperature, the contact angle of T700 carbon fibre bulk yarn before desizing is smaller than after desizing. This is because there are polar groups in the sizing agent such as hydroxyl, carbonyl and carboxyl, which helps increase the interaction between the carbon fibre bulk yarn and the resin, as the infiltration properties of the surface of the carbon fibre bulk yarn has improved. When the temperature rises, the contact angle of T700 carbon fibre bulk yarn shows a decreasing trend and then increases before desizing; however, the contact angle of T700 carbon fibre bulk yarn after desizing first increases and then decreases, because at high temperature, a certain level of curing reaction of the resin must have occurred, and the resin molecular weight increases, the distribution of molecular weight becomes wider, and the liquidity becomes poor. At the same time, decomposition of the surface sizing agent may also occur at a high temperature, which leads to a change in the properties of the sizing agent, thus resulting in a change in the surface contact angle for carbon fibre bulk yarn.

Conslusions

The three process parameters of spinning speed, nozzle pressure and nozzle diameter have a major influence on the yarn quality of carbon fibre bulk yarn. Different spinning process parameters will cause differences in yarn quality. The best preparation parameters for carbon fibre bulk yarn optimised using T700 carbon fibre tow as raw material and through orthogonal experimentation are as follows: nozzle air pressure 0.45 Mpa, spinning speed 150 m/min and nozzle diameter 2.2 mm.

The degree of disorder of T700 carbon fibre bulk yarn fibre is 18.70% ~ 25.60%. From the analysis and comparison of the ability to fix the resin of carbon fibre resin bulk with different degrees of bulking, it can be concluded that the more bouffant in the carbon fibre bulk yarn, the stronger the ability to fix the resin. Air spray processing causes no changes in the chemical properties of carbon fibres; hence the process of carbon original tows producing bulk yarns is a physical one.

At low temperature the contact angle of T700 carbon fibre bulk yarn before desizing is smaller than after desizing, and when the temperature rises, the contact angle of T700 carbon fibre bulk yarn shows a decreasing trend and then increases before desizing, while the contact angle of the T700 carbon fibre bulk yarn after desizing first increases and then decreases.

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