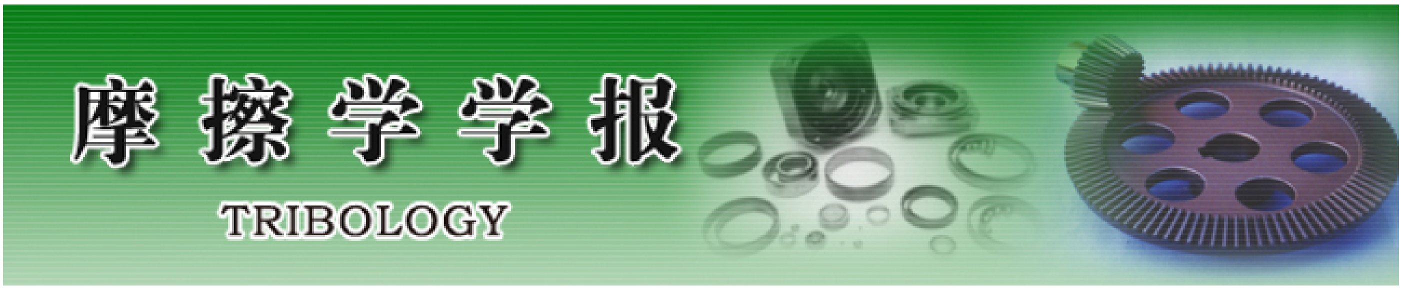

碳纤维束–圆辊细观接触行为研究

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碳纤维束-圆辊细观接触行为研究

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摘　要: 为探索碳纤维束-圆辊的接触机制，本文中采用自制摩擦模拟试验装置，结合薄膜压痕法分析了纤维束接触部位的三维(3D)表面形貌，研究了预加张力和接触角度对碳纤维束-圆辊接触面积的影响规律. 结果表明：碳纤维束-圆辊接触面内的纤维束取向度是影响接触面积的关键因素，当接触角度从60°增加到170°时，纤维束取向度逐渐减小，碳纤维束-圆辊接触面积也逐渐减小，且接触角度为60°时的接触面积是170°时的22倍；当预加张力从0.19 N增加到1.47 N时，纤维束取向度逐渐增大，碳纤维束-圆辊接触面积逐渐增大，且预加张力为1.47 N时的接触面积是0.19 N时的2倍. 在Hertz接触理论的基础上，考虑纤维束取向度建立碳纤维束-圆辊接触面积的理论预测模型，通过试验数据验证了该模型能够准确预测碳纤维束-圆辊的接触面积.

关键词: 碳纤维; 接触面积; 接触角度; 预加张力; Hertz接触
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Mesoscopic Contact Behavior between Carbon Tows and Round Roller

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Abstract: Textile composites have been widely used in aerospace, automotive, shipbuilding and construction fields due to their high specific strength, high specific modulus and high designability. Preform is the reinforced skeleton of textile composites, and tows, as the basic unit of preform, lose up to 5%~30% of its mechanical properties due to friction, compression and bending in the process of weaving and forming. Among them, the mechanical properties loss rate due to friction is as high as 9%~12%. However, researchers have conducted the friction and wear behavior of tows using different methods, the contact mechanism of tows in the process of friction and wear is still unclear. Different forming conditions of preforms will result in different contact surface morphology of tows, which seriously affects the mechanical property of preforms. Therefore, it is necessary for the study of friction mechanism to explore the contact mechanism between carbon tows and round roller. The contact area of tows is determined by the contact behavior of numerous fibers. Researchers have carried out a sea of research on the arrangement mode and mechanical properties of fiber in tows, but the quantitative relationship between the arrangement mode of fiber and the contact area of tows is rarely studied. In order to improve the prediction accuracy of tow's contact area, a self-designed experiment device was

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used in this paper. Combined with the thin film indentation method, three-dimension (3D) surface morphology of the contact surface of tows was analyzed, and the effect of different pre-tension and contact angle on the contact area between carbon tows and round roller was studied. In consideration of fiber orientation, the theoretical prediction model of the contact area between carbon tows and round roll was established. Experimental value, Hertz model and modified model were analyzed by the test of significance. The results showed that the orientation of tows in the contact surface was a key factor of the contact area. When the contact angle increased from 60° to 170°, the orientation of tows decreased gradually, the contact area between carbon tows and round roller decreased gradually, and the contact area at the contact angle of 60° was 22 times than 170°. When pre-tension increased from 0.19 N to 1.47 N, the orientation of tows increased gradually, the contact area between carbon tows and round roller increased gradually, and the contact area at the pre-tension of 1.47 N was about twice than 0.19 N. According to the probability of significance testing, the modified model could accurately predict the contact area between carbon tows and round roller. And it deemed friction behavior of tows should be studied by using the contact model considering the orientation of fiber in tows. As a key factor affecting the friction and wear behavior of the tows, the contact area of the tows was significant for the forming of composite materials. However, the contact behavior of tows and round roll was the result of the comprehensive influence of various factors. In this paper, the influence of different pre-tension and contact angle on the contact of tows was merely analyzed. In the future, the diameter of round roller, the roughness of the friction pair and the physical properties of tows will be discussed to further reveal the friction and wear mechanism of tows.

Key words: carbon tows; contact area; contact angle; pre-tension; Hertz contact

纤维增强复合材料因具有高比强度、高比模量和可设计性强等优点而广泛应用于航空航天、汽车、船舶和建筑工程等领域[1-5]. 纤维预制体是复合材料的增强骨架，而纤维束作为预制体的基本单元，在织造成型过程中因受到摩擦、压缩和弯折等导致的力学性能损失率高达5%~30%[6-9]. 其中，由于摩擦导致的性能损失率高达9%~12%[10-13]，因此，对纤维束在织造过程中摩擦磨损规律的研究成为关注的焦点.

目前，纤维束摩擦磨损常用的研究方法有平板抽拔法[14]、绞盘法[15]、旋转往复摩擦法[16-17]及正交线性往复摩擦法[18]等. 尽管研究人员采用不同方法对纤维束摩擦磨损行为进行了大量研究，但纤维束在摩擦磨损过程中的接触机制尚不明确. 因此，杨等[18]借助摩擦磨损试验仪和自制张力可控的摩擦试验夹具，研究了不同预加张力下碳纤维束的摩擦力F_f与接触面积A_n之间的相关性，证明两者正相关. Peng等[19]研究了碳纤维束摩擦损伤机制，表明纤维束间接触面积的变化是造成其磨损程度变化的主要因素. Cornelissen等[8]解释了平行接触条件下纤维束受到的摩擦力大于垂直接触条件下摩擦力的主要原因是接触面积较大. 基于以上研究结果得出纤维束接触面积是影响摩擦磨损行为的关键因素[20-22].

实际上纤维束接触面积是由若干根单丝的接触行为决定的，近年来针对束内单丝堆积方式和单丝的力学特性[23-26]，研究人员开展了一系列的研究. Bowden和Tabor等[27]发现纤维束受力后会发生迁移变形，这使得纤维束接触面内单丝排布极为复杂[28-29]. Mulvihill等[30]采用在玻璃片上涂覆半反射涂层的方法观测了单丝的接触面，发现随着法向负载的增大，单丝的接触面积与理论计算值之间差异明显. Tourlonias等[13]的研究结果表明单丝间具有粘合作用且单丝接触角度为0°时接触面积最大. 上述研究建立了单丝与纤维束接触面间的联系，证明了单丝的接触面积对纤维束接触面积有重要的影响[13,24,31]，但是单丝堆积方式与纤维束接触面积之间量化关系的研究较少.

为了研究单丝接触机制，提高纤维束接触面积的预测精度，本文中采用图像分析法计算了接触面内单丝取向度和单丝接触面积；使用自制摩擦模拟试验装置，研究了不同接触角度与预加张力条件下碳纤维束-圆辊之间的接触面积变化规律；考虑单丝取向度建立了碳纤维束-圆辊接触面积的理论预测模型，为织造过程中摩擦磨损研究提供理论基础.

1　试验部分

1.1　试验材料

纤维束采用由威海拓展纤维有限公司制造的碳纤维束(TZ-12K)，其性能指标列于表1中. 硅胶薄膜采用由佛山名明宸达有机硅有限公司生产的MCD有机硅胶(固化比1:5).

1.2　试验设备

由图1(a)中试验装置示意图所示，支架将固定辊、接触辊与导纱辊连接为1个整体，固定辊与导纱辊位于同一水平面且等距分布在接触辊两侧，试验时，纤维束两端分别与固定辊和砝码连接，中段与接触辊和

表 1　碳纤维束性能指标

Table 1　Performance index of carbon tows

Sample	Young’s modulus/GPa	Fiber diameter/μm	Number of tows	Tensile strength/MPa	Width/mm
TZ-12K	300	7.2	12 000	5 500	5±0.5

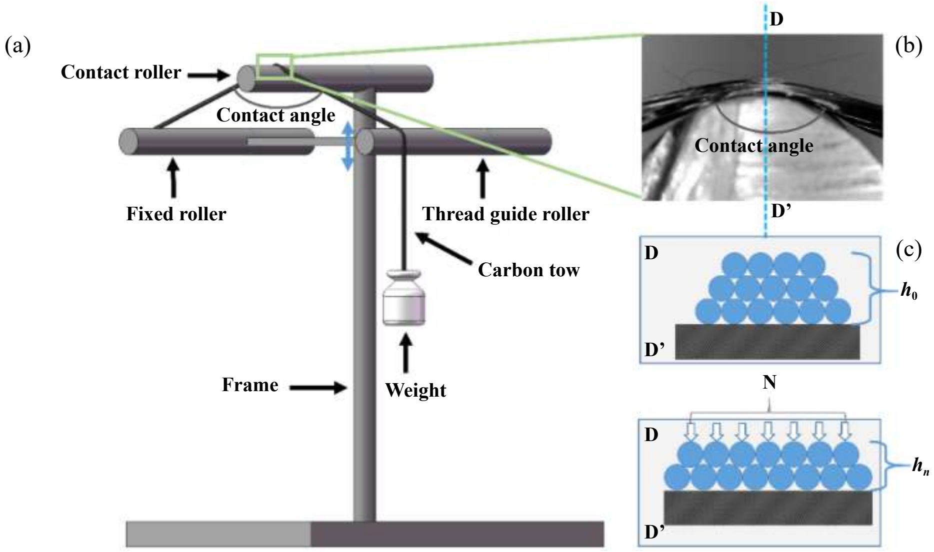


Fig. 1 Experimental rig: (a) schematic of the experimental rig; (b) schematic of tows mesoscopic contact; (c) schematic drawing of tows mesoscopic contact

图 1　试验装置: (a)试验装置示意图; (b)接触区域局部放大图; (c)细观接触示意图

导纱辊接触. 通过调节接触辊的高度改变接触角度，采取加载不同重量砝码的方式调节纤维束预加张力. 接触区域局部放大图如图1(b)所示，由于接触条件不同，导致纤维束内单丝排列方式发生变化，如图1(c)所示.

1.3　试验方法

在本文中基于既往纤维束接触面研究[3,18-19]，进行如图2所示的纤维束接触面提取试验. 如图2所示，将硅脂与固化剂按照1∶5制备硅胶薄膜，取约2 ml混合液滴至接触辊表面并均匀涂抹，纤维束与接触辊接触8 min后剥离纤维束，获得携带纤维束接触面信息的硅胶薄膜，通过3D轮廓测量仪(VR-5200，日本)对硅胶薄膜进行分析. 上述操作均在温度25±5 ℃和湿度40%~50%条件下进行.

根据织造工艺及预制体成形条件确定预加张力

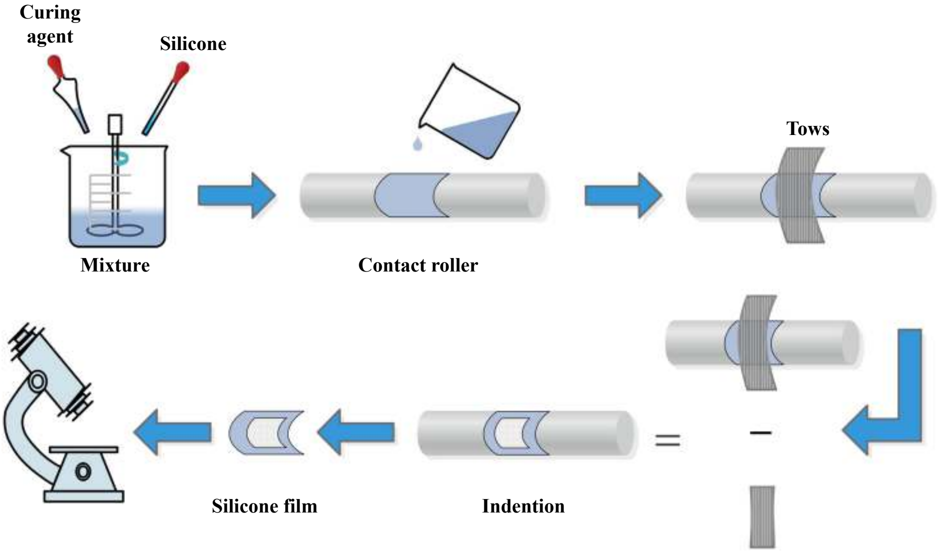


Fig. 2 Experimental method for extracting fiber contact surface

图 2　接触面提取试验方法

和接触角度[18]，试验参数列于表2中，为验证试验的可靠性，同一接触条件下进行5次试验.

表 2　试验参数

Table 2　Main parameters of experiment

Serial number	Contact angle/(°)	Pre-tension/N	Length of tows/cm
0	–	–	–
1	60	0.98	50
2	90	0.98	50
3	130	0.98	50
4	150	0.98	50
5	170	0.98	50
6	150	0.19	50
7	150	0.39	50
8	150	1.47	50

1.4　分析方法

1.4.1　接触面积处理方法

本研究中采用图像分析法来观测纤维束接触面的变化情况，通过VR-5200 Analysis软件对碳纤维束-圆辊接触面积进行测量. 分析前，首先将每幅图像的像素大小转换为以毫米为单位的物理长度，再将其转换为灰度图以完成图像比例设置. 图3(a~c)展示接触面提取方法，根据Cornelissen等[8]提出的纤维束摩擦磨损试验接触力学模型可知，纤维束在不同接触条件下表现为单丝从未接触层向接触层迁移，如图1(c)所示.

阈值作为判断接触层与未接触层的重要参数，为准确选择接触单丝，采用图1(a)所示试验装置对纤维束径向高度进行测量，将原样值与测量值之差作为纤维束接触面的图像阈值U，重复此分析，计算所有接触条件下的图像阈值. 通过图像阈值将实际接触区域提出分析，如图3(c)所示. 随后将接触区域每0.5 mm做一次分割，分为若干幅轮廓图像，如图3(d)所示，根据每幅轮廓图中的波动特性，采用“Image J”软件对每根接触单丝进行重构，绘制接触单丝空间路径[图3(e)]并定义如下表征参数.

单丝与分割线交于O与a_{i+1}，过O点作单丝的投影Oa_i，Oa_{i+1}与Oa_i夹角为分割点间取向度，记β_i，如图3(f)所示.

1.4.2　取向分析方法

如图4所示，本文中将接触面内接触单丝取向度β_{fiber}按式(1)进行归一化处理.

$$\beta_{\text{fiber}} = \sum_{i=1}^{n} \beta_i / n \qquad (1)$$

其中：β_i为接触单丝分割点间取向度；n为分割数量.

为进一步分析纤维束取向度，按照接触单丝的处理方式，将纤维束取向度β_{tows}按照式(2)进行归一化处理.

$$\beta_{\text{tows}} = \sum_{i=1}^{m} \beta_{\text{fiber}} - 180 \times t \qquad (2)$$

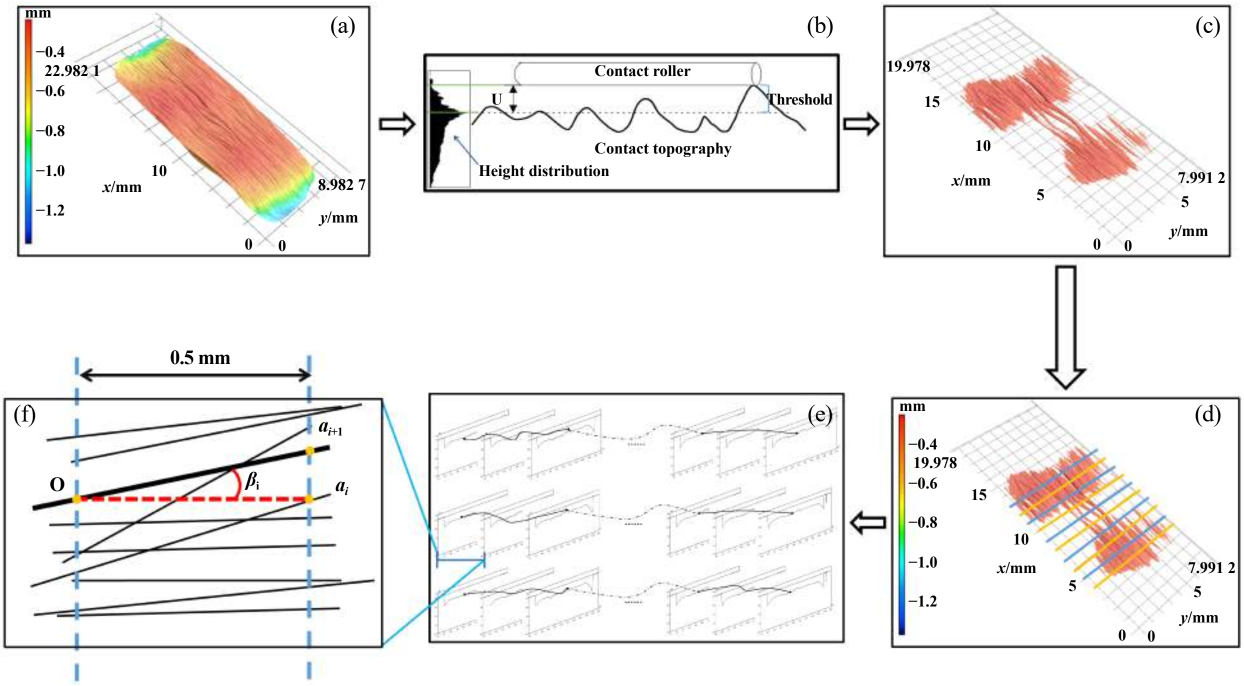


Fig. 3 Contact analysis method

图 3　纤维束接触面分析方法

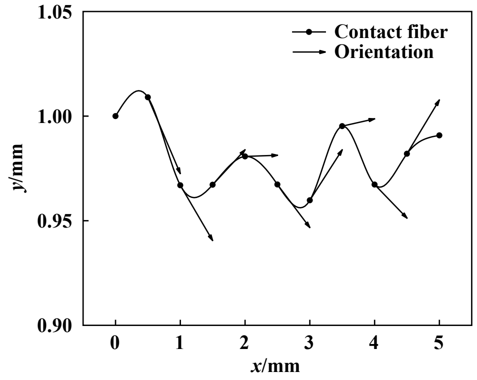


Fig. 4 Schematic of contact fiber track

图 4 接触单丝轨迹图

其中：β_{fiber}为单丝取向度；t为归一化系数；m为接触单丝根数.

$\beta_{\text{tows}}=0$表示纤维束在接触条件下不发生偏转，$\beta_{\text{tows}}=\pm180°$表示纤维束在接触条件下发生反向偏转.

2 结果与分析

2.1 接触角度对接触面积的影响

经过归一化处理后，得到不同接触角度下接触单丝取向变化曲线，如图5所示. 图中单柱分布在0轴两侧，正和负分别代表接触单丝顺时针和逆时针偏移，单柱高度代表接触单丝取向度. 由图5(a~e)可知，随着接触角度减小，单柱数量增多，即接触单丝增多.

图6示出纤维束取向度随接触角度的变化关系，随接触角度增大，纤维束取向度逐渐减小，这是由于接触角度较大(170°)时，表层与里层的接触单丝数量差异显著，里层单丝受到其它层单丝挤压束缚，自由度低，里层单丝充分接触圆辊，取向度减小的现象.

采用图像分析方法的关键是阈值，阈值选取过小会产生噪点，过大又会造成图像中的非噪点信号被视为噪点而过滤掉，同一张接触面图像阈值不同，接触面积也不同. 由图7可知，纤维束径向高度随接触角度增大而增大，这是由于接触角度增大，接触单丝数量减少，导致束内单丝越层现象不明显. 此现象可以用纤维重新排列理论解释[25]，纤维束内的单丝在不同接触角度条件下相互滑移，重新排列组合形成新的纤维束接触面，导致接触单丝数量减少，内层单丝无法迁移至接触层，纤维束径向高度增大. 因此，采用图像分析方法测算碳纤维束-圆辊接触面积时，应采用如公式(3)计算阈值，消除干扰计算面积的噪点与表面杂质.

$$U_\alpha = h_{\mathrm{o}} - h_\alpha \qquad (3)$$

其中：U_α为接触角度为α条件下的阈值；h_0为无接触条

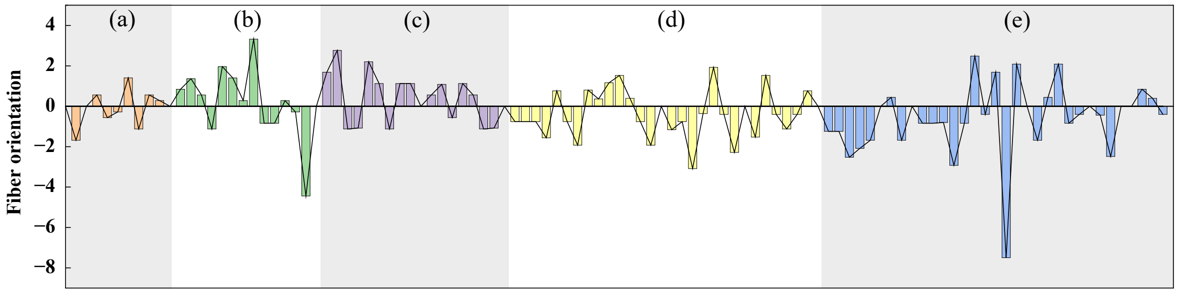


Fig. 5 Distribution of fiber orientation with pre-tension of 0.98 N (contact angle: a-170°; b-150°; c-130°; d-90°; e-60°)

图 5 预加张力0.98 N条件下，接触单丝取向度分布(接触角度: a-170°; b-150°; c-130°; d-90°; e-60°)

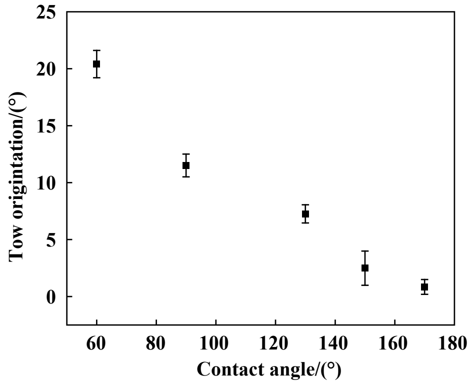


Fig. 6 Influence of different contact angle on tows orientation

图 6 不同接触角度对纤维束取向度的影响

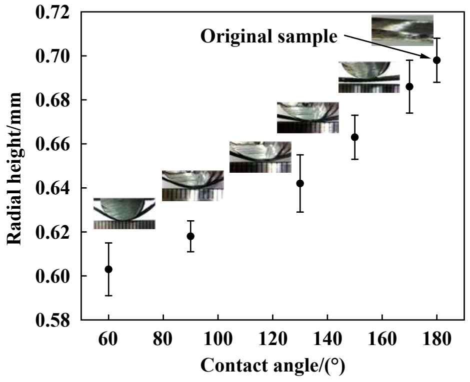


Fig. 7 Influence of different contact angle on radial height of tows

图 7 不同接触角度对纤维束径向高度的影响

件下纤维束径向高度；h_α为接触角度为α条件下纤维束径向高度.

图8为不同接触角度碳纤维束-圆辊接触面形貌图，从图8(a)中可清晰看到接触单丝的痕迹，且接触面轮廓呈“工”型分布，这可能是由于在接触过程中，纤维束张力不匀，张力较大的单丝优先跃迁到接触层与圆辊接触. 从图8(c)中可以看出，当接触角度增加到130°时，接触面长度明显减小，且接触面形貌呈长方形，是碳纤维束-圆辊接触面的典型形状[19].

图9所示为不同接触角度条件下碳纤维束-圆辊接触面积的变化趋势图，当接触角度为60°时，接触面积为119.48 mm^2，接触角度增大至130°时，接触面积为47.42 mm^2，接触角度继续增大至170°时，接触面积约为5.34 mm^2. 当摩擦角度在60°~170°范围变化时，碳纤维束-圆辊接触面积随接触角度的增大而逐渐减小，接触角度为60°的接触面积是接触角度为170°的22倍.

2.2　预加张力对接触面积的影响

图10为纤维束接触角度为150°条件下，单丝取向度随预加张力变化的直方图，根据纤维束预加张力不同可分为(a)、(b)、(c)和(d)四组，分别代表预加张力为0.19、0.39、0.98和1.47 N单丝的取向度分布. 类似接触角度与取向度变化规律，图10表明单柱数量随预加张力增大而逐渐增多，即接触单丝增多.

图11示出纤维束取向度随预加张力的变化关系，

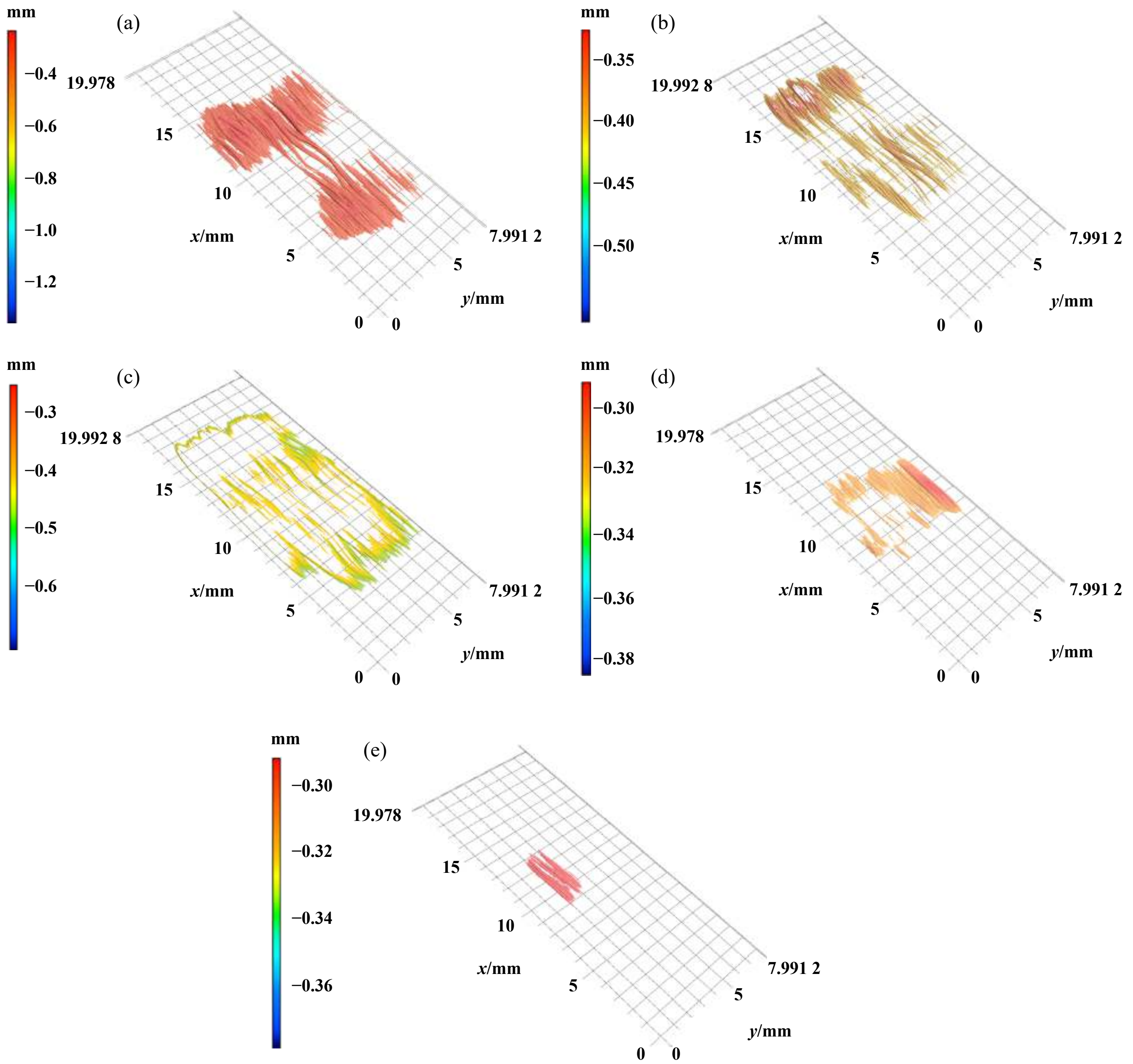


Fig. 8 Contact surface of tows under different contact angle (contact angle: a-60°; b-90°; c-130°; d-150°; e-170°)

图 8　不同接触角度下纤维束-圆辊接触(接触角：a-60°; b-90°; c-130°; d-150°; e-170°)

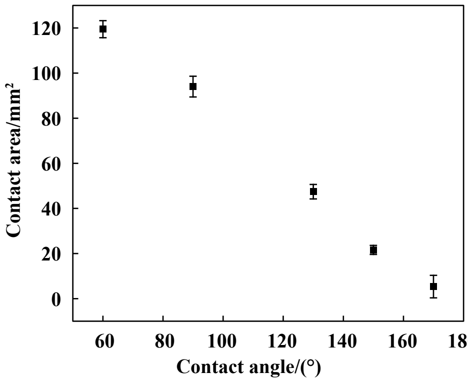


Fig. 9 Contact area under different contact angle

图 9 不同接触角度下碳纤维束-圆辊接触面积

随着预加张力的增大，纤维束取向度逐渐增大，且增大效果明显，这可能是由于预加张力增大，碳纤维-圆辊接触面法向分力增大，排布在里层的单丝受到挤压，向外层迁移，导致接触层单丝数量增多，接触面变宽，进而纤维束取向度逐渐增大. 预加张力不仅影响纤维束取向度，同时也将导致纤维束径向高度的变化. 图12为不同预加张力纤维束径向高度的变化曲线. 类似接触角度的变化机制，随预加张力增大，碳纤维束-圆辊接触面法向分力增大，里层单丝跃层现象明显，由此产生纤维束径向高度随预加张力的增大而减小的现象.

如图13所示，在不同预加张力条件下，碳纤维束-圆辊接触面呈不对称分布，此现象可以用单丝重新排列理论解释[25]，主要是由于纤维束内的单丝在不同接触条件下相互滑移，重新排列组合形成新的纤维束接触面. 具体接触面积如图14所示，当预加张力为0.19 N时，接触面积为13.02 mm^2，预加张力增加为1.47 N时，接触面积为24.3 mm^2，增幅为46.4%. 预加张力为1.47 N时的接触面积约为预加张力为0.19 N时的2倍. 当预加张力小于0.19 N时，接触区域存在明显的不连续现象，随着预加张力的增大，碳纤维束-圆辊接触面内的不连续现象逐渐消失，其形貌变得愈发平整，接触面接近典型形状[19]. 这是由于在较小预加张力条件下，纤维束表层与里层单丝堆积松散，随预加张力增大，单丝堆积紧密，接触面不连续现象逐渐消失.

2.3 接触面积模型

2.3.1 Hertz接触模型

文中采用Hertz接触理论[13]模型验证试验测得的碳纤维束-圆辊接触面积. 假设单丝是光滑的圆柱体，

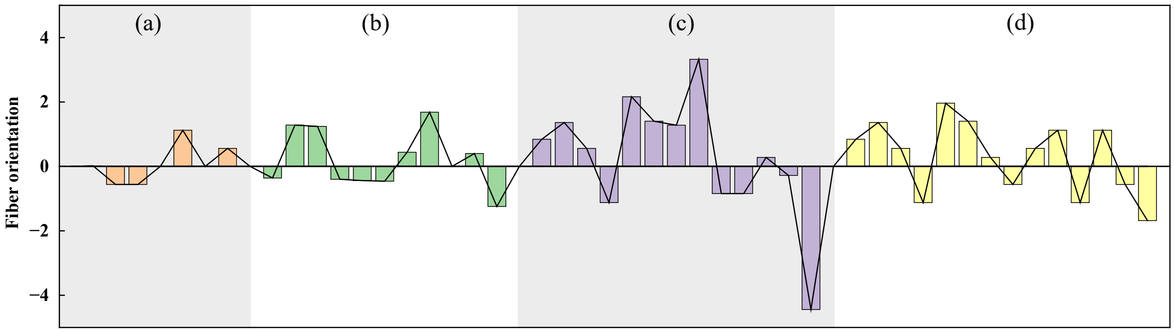


Fig. 10 Distribution of fiber orientation with contact angle of 150° (pre-tension: a-0.19 N; b-0.39 N; c-0.98 N; d-1.47 N)

图 10 接触角度150°条件下，接触单丝取向度分布(预加张力：a-0.19 N; b-0.39 N; c-0.98 N; d-1.47 N)

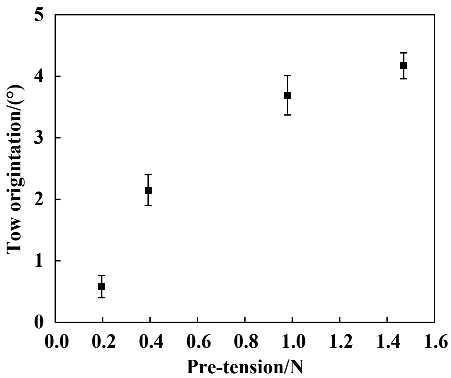


Fig. 11 Influence of different pre-tension on tows orientation

图 11 不同预加张力对纤维束取向度的影响

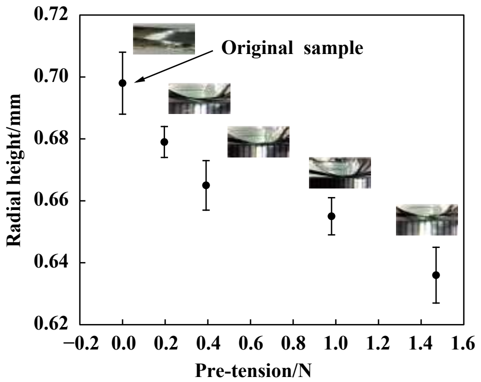


Fig. 12 Influence of different pre-tension on radial height of tows

图 12 不同预加张力对纤维束径向高度的影响

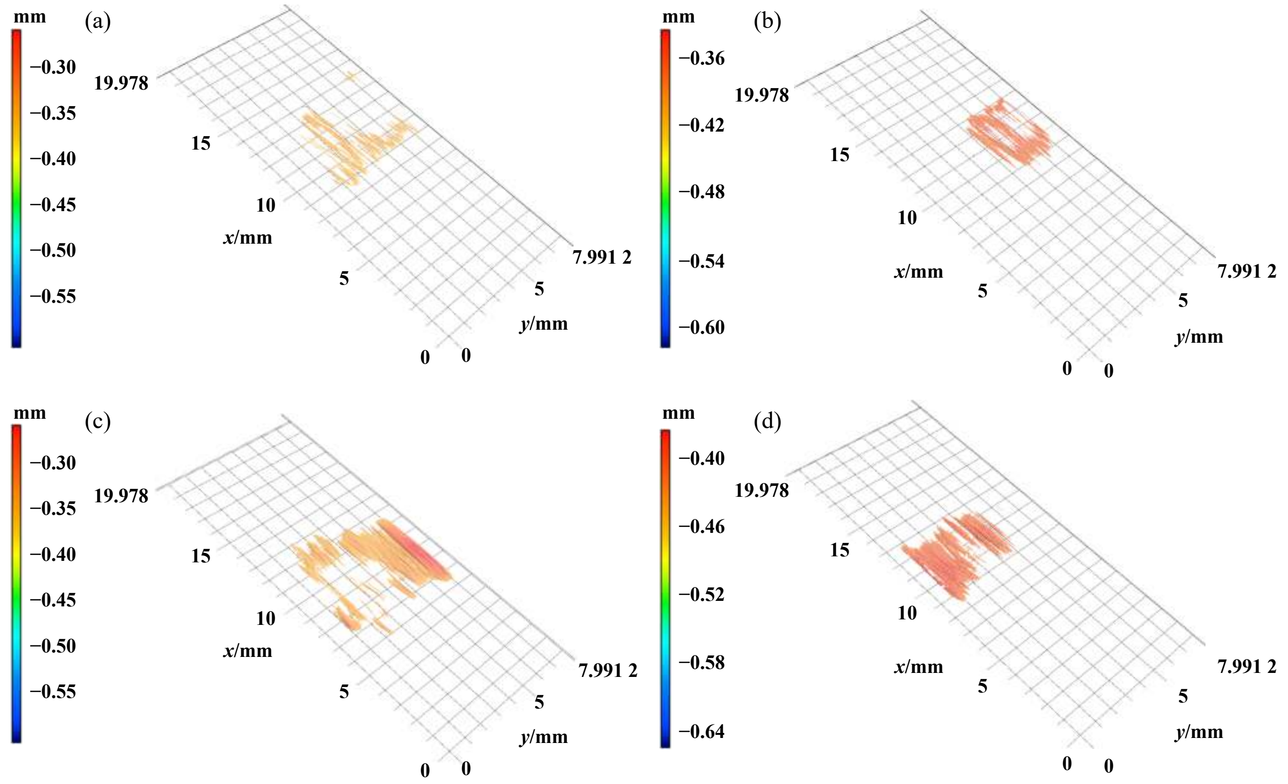


Fig. 13 Contact surface of tows under different pre-tension (a-0.19 N; b-0.39 N; c-0.98 N; d-1.47 N)

图 13　不同预加张力条件下纤维束-圆辊接触面(a-0.19 N; b-0.39 N; c-0.98 N; d-1.47 N)

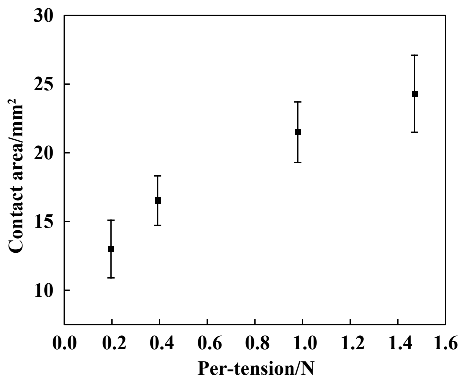


Fig. 14　Contact area under different pre-tension

图 14　不同预加张力下碳纤维束-圆辊接触面积

且纤维束中单丝都是平行排列的，单丝与接触辊之间的接触半宽度按式(4)[30, 32]计算.

$$a = \left(\frac{3N_{\mathrm{fil}}R^*}{4E^*}\right)^{\frac{3}{2}} \tag{4}$$

其中：N_{fil}为作用在单丝上的法向负载；R^*为接触体的等效半径；E^*为等效杨氏模量，表示为式(5).

$$\frac{1}{E^*} = \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2} \tag{5}$$

其中：E_1和E_2为单丝与接触辊的弹性模量；v_1和v_2为单丝与接触辊的泊松比.

由于杨氏模量与泊松比的值较难获得，并且关于该主题的参考文献较少，因此，将现有研究中的数据平均值作为本文的参考值[13,18-19,33]，即杨氏模量的参考值为17 GPa，泊松比为0.31.

由于接触时单丝发生形变，故等效半径R^*的表示为式(6)[34-35].

$$\frac{1}{R^*} = \frac{1}{R_1} + \frac{1}{R_2} \tag{6}$$

其中：R_1和R_2为单丝与接触辊的曲率半径.

单丝接触面积表示为式(7).

$$A = 2aL \tag{7}$$

其中L为接触面长度，表示为式(8).

$$L = \frac{(180-\theta)\pi r}{180} \tag{8}$$

其中：θ为接触角度；r为接触辊半径.

法向负载N计算公式见式(9).

$$N = F\int \cos\left(90-\frac{\theta}{2}\right)\mathrm{d}\theta = F\int \sin\frac{\theta}{2}d\theta \tag{9}$$

其中：F为纤维束预加张力.

根据Mulvihill等[30]的研究可知碳纤维束-圆辊理论接触面积按照式(10)计算.

$$A_n = An_{\rm fil} \tag{10}$$

其中：$n_{\rm fil}$为接触单丝数，表示为式(11).

$$n_{\rm fil} = \frac{D}{d} \tag{11}$$

$$N_{\rm fil} = \frac{N}{n_{\rm fil}} \tag{12}$$

其中：D为纤维束宽度；d为纤维单丝直径.

表3列出Hertz接触理论模型计算得出的碳纤维束-圆辊接触面积.

表 3 不同接触条件碳纤维束-圆辊Hertz理论接触面积

Table 3 Hertz contact area between carbon tows and round roller under different contact condition

Contact parameter	Parameter value	L /mm	R^* /mm	E^* /GPa	a /mm	A_n /mm^2
Contact angle/(°)	60	12.54	3.6×10^{-3}	17.39	6.38×10^{-3}	106.61
	90	9.40			5.60×10^{-3}	74.74
	130	5.22			4.20×10^{-3}	34.98
	150	3.13			2.87×10^{-3}	17.82
	170	1.04			1.50×10^{-3}	4.13
Pre-tension/N	0.19	3.13	3.6×10^{-3}	17.39	1.48×10^{-3}	10.42
	0.39	3.13			1.92×10^{-3}	13.13
	0.98	3.13			2.87×10^{-3}	17.82
	1.47	3.13			3.33×10^{-3}	20.40

图15是不同接触角度与预加张力条件下，Hertz接触理论与试验测得的接触面积的变化曲线. 两者呈相同变化趋势，即接触面积随接触角度的增大而减小，随预加张力增大而增大. 利用相关性分析方法研究Hertz接触理论模型与试验之间的相关关系，得到Pearson相关系数均大于0.995，并且显著水平(p值)均小于0.01，因此可以说明试验可以较好反映碳纤维束-圆辊接触行为.

但是相比较而言，两者之间还存在一些差异，如图15(a)所示，在接触角度为130°~170°范围内Hertz接触理论值与试验值具有高相似度，这是由于在大接触角度条件下，接触单丝取向度低，碳纤维束-圆辊接触面积受取向度影响不明显. 在60°~130°范围内Hertz接触理论值与试验值差异明显，这是由于在小接触角度条件下，接触面变宽，束内单丝分散，单丝取向度高，碳纤维束-圆辊接触面积受取向度影响明显. 如图15(b)所示，随着预加张力增大，Hertz接触理论值与试验值的差异逐渐增大，这是由于在小预加张力条件下单丝取向度小，接触单丝长度近似等于无取向单丝长度，即纤维束取向度对预加张力的影响较小. 综上得出：纤维束取向度是影响碳纤维束-圆辊接触面积的关键因素，接触角度与预加张力影响了接触面内纤维束取向度，改变了碳纤维束-圆辊接触面积.

2.3.2 接触面积改进模型

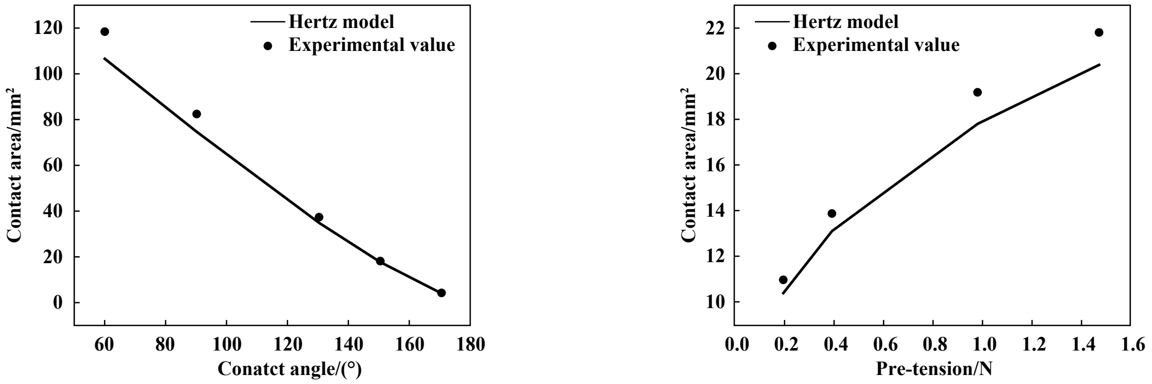
为改进因纤维束取向度导致Hertz接触理论计算值与试验测量值之间的差异，通过式(13)计算改进等效半径R'.

$$\frac{1}{R'} = \left(\frac{1}{R_1^2} + \frac{1}{R_2^2} + \frac{2}{R_1R_2}\cos(2\beta_{\rm tow})\right)^{\frac{1}{2}} \tag{13}$$

L'为改进接触面长度，表示为式(14).

$$L' = \frac{(180-\theta)\pi r}{180} \times \sec\beta_{\rm tow} \tag{14}$$

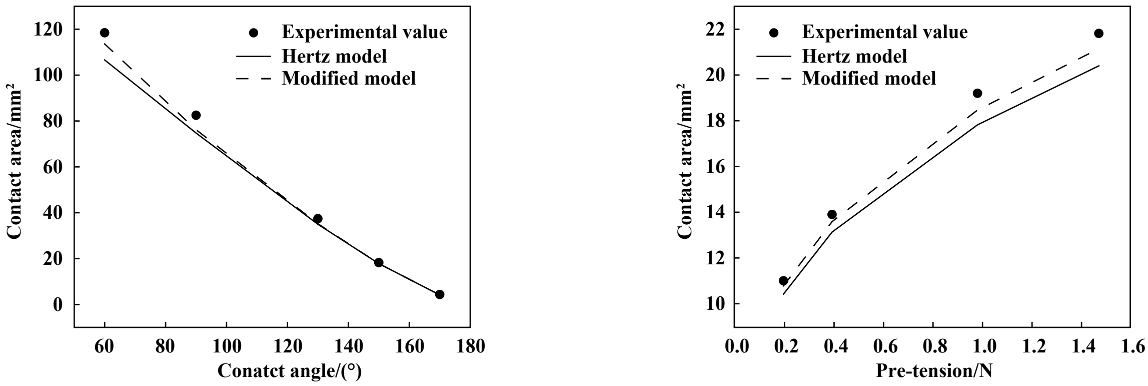
将改进接触面长度L'与等效半径R'代入式(4)得到接触半宽度a，进而得到碳纤维束-圆辊接触面积$A_{\rm n}$，表4列出了考虑纤维束取向度的改进模型参数值. 图16为Hertz接触模型、改进模型和试验的接触面积变化曲线，由图16可知，三种模型所得的接触面积随接触角度与预加张力的变化均呈相同趋势，显然，改进模型与



(a) Contact angle (b) Pre-tension

Fig. 15 Comparison of Hertz model and experiment contact area under different contact angle and pre-tension

图 15 不同接触角度与预加张力条件下理论和试验接触面积的比较



(a) Contact angle　　(b) Pre-tension

Fig. 16 Hertz model, modified model and experiment contact area under different contact angle and pre-tension

图 16　不同接触角度与预加张力条件下Hertz接触模型、改进模型与试验所得接触面积

表 4　不同接触条件碳纤维束-圆辊改进接触面积

Table 4　Modified contact area between carbon tows and round roller under different condition

Contact Parameter	Parameter value	L'/mm	R'/mm	A_n/mm^2
Contact angle/(°)	60	13.38	$3.583\,7\times10^{-3}$	113.61
	90	9.60	$3.580\,2\times10^{-3}$	76.15
	130	5.27	$3.579\,2\times10^{-3}$	35.20
	150	3.14	$3.578\,6\times10^{-3}$	17.81
	170	1.05	$3.578\,5\times10^{-3}$	4.13
Pre-tension/N	0.19	3.13	$3.578\,9\times10^{-3}$	10.78
	0.39	3.14	$3.578\,7\times10^{-3}$	13.59
	0.98	3.14	$3.578\,6\times10^{-3}$	18.47
	1.47	3.14	$3.578\,5\times10^{-3}$	21.15

试验的吻合性较好，通过Tukey显著性检验方法对三种模型进行分析，其检验参数列于表5中.

由表5可知，在两类接触条件下，Ex-Hertz的Tukey检验概率均小于Ex-Mod的Tukey检验概率. 这说明改进模型较Hertz接触模型与试验模型更具有一致性，因此在纤维束接触行为研究过程中，应采用考虑纤维束内单丝取向度的接触模型，进行纤维束摩擦磨损行为的研究.

表 5 不同接触条件下Tukey检验参数

Table 5 Tukey-test parameters of three models under different contact condition

Contact Parameter	Tukey-test probability	
	Ex-Hertz	Ex-Mod
Contact angle	0.87	0.92
Pre-tension	0.77	0.89

Note: Ex-Hertz represents experiment and Hertz model; Ex-Mod represents experiment and modified model

3　结 论

a. 纤维束取向度是影响碳纤维束-圆辊接触面积的关键因素，接触角度与预加张力影响了接触面内纤维束取向度，改变了碳纤维束-圆辊接触面积.

b. 当接触角度从60°增加到170°时，纤维束取向度逐渐减小，碳纤维束-圆辊接触面积也逐渐减小，且接触角度为60°时的接触面积是170°时的22倍；当预加张力从0.19 N增至1.47 N时，纤维束取向度逐渐增大，碳纤维束-圆辊接触面积逐渐增大，且预加张力为1.47 N时的接触面积是0.19 N时的2倍.

c. 基于Hertz接触理论，考虑纤维束取向度建立了碳纤维束-圆辊接触面积的改进模型，通过试验数据验证了改进模型与试验结果高度吻合.

综上所述，纤维束接触面积作为影响其摩擦磨损行为的关键因素，对复合材料成型加工具有重要意义. 但纤维束-圆辊接触行为是由各个因素综合影响的结果，而本文中仅分析了不同预加张力和接触角度对纤维束接触面的影响. 因此，后续需要加入对圆辊直径、摩擦副粗糙度以及纤维束物理性能等方面的探讨，进一步揭示纤维束摩擦磨损机理.

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