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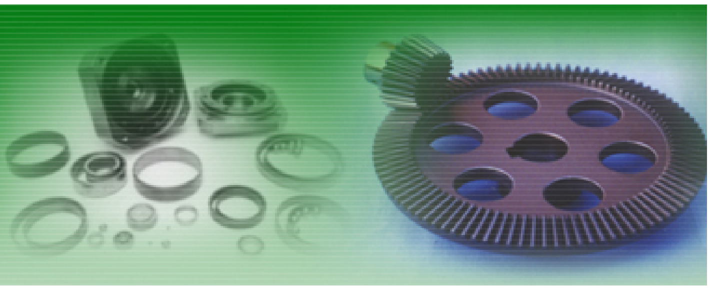

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纺织复合材料预制体成形过程纤维束摩擦行为研究进展

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摘　要: 预制体是复合材料的增强骨架，由成千上万根纤维束织造而成. 预制体中的纤维束由于织造过程中的交织运动会发生不同程度的摩擦损伤，而纤维的磨损会导致预制体力学性能损失率高达9%~12%. 因此，揭示纤维束在织造过程中的摩擦磨损机理对提升预制体力学性能具有重要意义. 本文中综述了近年来有关纤维束摩擦行为的研究进展：首先，概述纤维束-金属和纤维束-纤维束摩擦测试方法的优缺点；其次，分析得出摩擦角度、摩擦频率、预加张力和法向载荷对纤维束摩擦性能的影响机制；最后，总结纤维束摩擦磨损行为的理论分析模型. 本综述中对复合材料预制体成形工艺设计和纤维束摩擦损伤的量化分析具有指导意义.

关键词: 纺织复合材料; 预制体; 成形过程; 纤维束; 摩擦磨损
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A Review of Fiber Yarn Friction in the Forming Process of Textile Composite Preforms

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Abstract: Preforms are the reinforcements of textile composites, which directly affect the mechanical properties of composite materials. Three-dimensional(3D) preforms are often made into composites with excellent mechanical properties and low mass. Compared with 2D preforms, the delamination resistance and impact damage tolerance of the composites can be significantly improved. 3D preforms can be used to quickly produce near-net complex-shaped components, e.g. radome, rocket throat and multi-tube bracket, using varieties of high-performance fiber materials (e.g. carbon, aramid, UHMPEF). However, fiber is the basic unit of the preform. Friction and wear of fiber/tows is a common problem during 3D performs forming process. The research shows that the loss rate in the mechanical properties of the preforms is as high as 5%~30% due to friction, compression and bending. Among them, the loss rate caused by friction is as high as 9%~12%. For example, during the beating-up stage of the 3D orthogonal weaving process, tows are

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subjected to friction and wear, resulting in a large amount of hairiness in the preforms, which leads to result in the decline of mechanical properties and design limitations of the composite. At present, in order to meet design requirements, production departments are forced to use high-cost fibers to compensate for defects. Therefore, it is of significance to research the friction and wear behavior of fiber/tows in the forming process of complex 3D preforms, which will contribute to improving the mechanical properties and service life of the composites and reduce the maintenance cost. Since the 1980s, researchers from Britain, France and the United States have engaged in the friction and wear behavior of tows by reciprocating friction method, pull-out method and capstan friction method. However, the friction research of fiber\tows started late in China, and some research institutions mainly focus on improving its wear resistance during fiber production. The research about contact deformation, friction and wear mechanism of tows with complex structure preforms is still lack of in-depth work. Therefore, it is important to reveal the friction and wear mechanism of tows in the weaving process and improve the comprehensive property of preforms. In this review, the recent researches on the friction behavior of tows-metal and tows–tows are reviewed. Firstly, the advantages and disadvantages of tows-metal and tows-tows friction testing methods are summarized. Secondly, the influence mechanism of angle, frequency, pretension and normal load on the friction performance of tows is analyzed. Finally, the theoretical analysis model of tows of friction and wear is summarized. This review has a certain guiding significance for forming process and quantitative analysis of friction and wear of textile composite preforms.

Key words: textile composite; perform; forming process; tows; friction and wear

纺织复合材料具有比强度高、比模量大、耐疲劳、耐腐蚀和结构可设计性强等众多优点，已在航空航天、交通运输及海洋船舶等工业中得到广泛应用[1-2]. 随着纺织复合材料工业的发展[3-7]，人们对材料的力学性能提出了更高的要求，三维(3D)纤维结构预制体增强纺织复合材料因其优异的抗分层、抗冲击损伤和近净成型等特点逐渐成为研究热点[8-12]. 但是，3D预制体成形及损伤的相关研究表明[13-16]，因纤维束(纱线)的摩擦、压缩及弯折等作用导致预制体力学性能损失率高达5%~30%[17-21]，其中，纤维束摩擦导致的性能损失率可达9%~12%[13, 22-24]. 例如，在3D机织工艺的“打纬”阶段，钢筘将纬纱打向织口，经纬纱紧密交织，纤维束在此过程中反复摩擦，磨损不断积累，在预制体表面可以观察到大量“毛羽”，这将造成复合材料力学性能的下降[25]. 因此，研究3D纺织预制体成形过程中纤维束的摩擦磨损行为，对量化评估纤维束损伤、优化3D纺织预制体成形工艺以及提高复合材料力学性能具有重要意义[26-30].

针对纤维束的摩擦测试最早开始于19世纪70年代，最初采用两根纱线相互扭曲的方式进行测试[31]. 根据接触方式可将纤维束摩擦行为分为三种类型[32]：点接触型[24, 33-36]，即纤维或纤维束与粗糙平面发生摩擦，由多个峰值点形成的多点接触；线接触型[37-39]，即纤维束内纤维之间发生滑动摩擦；面接触型[40-41]，即纤维束与接触面发生滑动摩擦. 向忠等[32]综述了纤维摩擦学的研究进展，分析了上述不同类型摩擦测试方法的特点和适用范围. 在此基础上，研究人员进一步对纤维束摩擦行为进行研究[25, 28, 42](表1中对常用摩擦测试方法适用范围及优缺点进行了总结)，并设计了符合实际工况的试验方法[34, 37, 43-44]与建模方案[23, 45-48]. 图1所示为近10年来纺织复合材料预制体成形过程中纤维束摩擦学的文献报道情况、发文量及被引量，表明

表 1　常用摩擦测试方法适用范围及优缺点

Table 1　Application scope, advantages and disadvantages of friction test methods

Way of friction	Range of application	Advantages	Disadvantages	Representative papers
Reciprocating friction	Tows-tows Tows-tool	Easy to design	Fluctuates significantly Difficult to control tension	[44, 50−54]
Capstan friction	Tows-tool Tows-tows	Easy to operate, high accuracy, easy to control speed	Difficult to control environment condition	[33, 43, 55]
Pull-out test	Tows-tows Tows-tool	Unrestricted specimen size	Difficult to control speed	[37−40, 56−58]
Fiber twist method	Tows-tows	Easy to obtain contact surface	Difficult to operate	[59−60]
Hanging fiber method	Tows-tows Tows-tool	Easy to operate, simple in structure	Fluctuates significantly, difficult to improve accuracy	[24, 35−36]

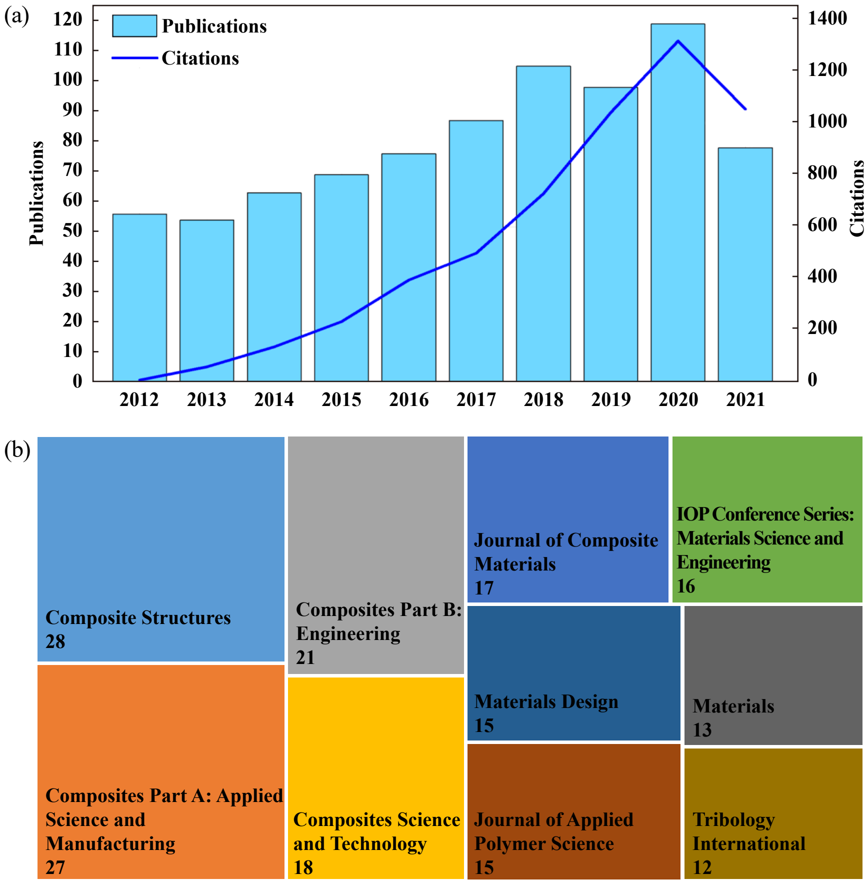

Fig. 1 Research progress of friction methods during textile composites forming for tows in recent 10 years: (a) published items and citations in each year; (b) key publications of friction methods during textile composites forming for tows [obtained from the Web of Science Core Collection with the following keywords: friction methods, tows and fiber (check on 6 SEP 2021)]

图 1 近10年关于纤维束摩擦学的文献报道情况：(a)年出版数及年引用数；(b)在纺织复合材料成型中摩擦测试方法相关文献的主要期刊来源

纤维束的摩擦性能正逐渐受到人们的重视，成为1个热点问题[40-41, 49].

本文中综述预制体成形过程中的纤维束摩擦学研究，总结了纤维束-金属和纤维束-纤维束摩擦性能测试方法的优缺点，分析得出摩擦角度、摩擦频率、预加张力和法向载荷等因素对纤维束摩擦性能的影响机制，总结了纤维束摩擦磨损行为的理论分析模型，为纤维束摩擦机理研究及预制体成形工艺优化提供帮助，综述路线如图2所示.

1 纤维束摩擦测试方法

纺织预制体成形过程中的摩擦行为主要分为两类，第一类是纤维束与钢筘、综丝和导纱辊等金属构件之间的摩擦；第二类是经纱、纬纱和法向纱等不同纤维束系统之间的摩擦. 因此，研究人员对纤维束摩擦学的研究主要包括纤维束-金属和纤维束-纤维束摩擦两种类型[35, 50, 61-63]，本节中对近年来纤维束摩擦测试方法及设备的发展进行综述.

1.1 纤维束-金属摩擦测试

在预制体成形过程中，纤维束与织机构件的摩擦作用对纤维束产生不可恢复的磨损，进而对预制体及其复合材料的力学性能产生不利影响，纤维束-金属摩擦测试方法及测试装置的发展为纤维束在复杂工况下摩擦磨损行为的研究奠定了基础[64-65].

抽拔法是纤维束-金属摩擦性能测试的重要方法[61]，如图3(a)所示，纤维束在一定法向压力条件下从平板中抽出所需的力为摩擦力F_c[66]，然后根据Coulomb理论即可获得摩擦系数. 该方法可表征预制体成形过程中纤维束在不同细度、预加张力及摩擦频率等条件下的摩擦性能. 近年来，国内外研究人员采用抽拔法对纤维束摩擦学特性进行了大量研究，得到了众多有利于工程实践的结论. Mulvihill等[37]对碳纤维束与粗糙度为0.005~3.2 μm的金属平板间的摩擦行为进行了研究，并记录了纤维束-金属平板接触时的摩擦力F随

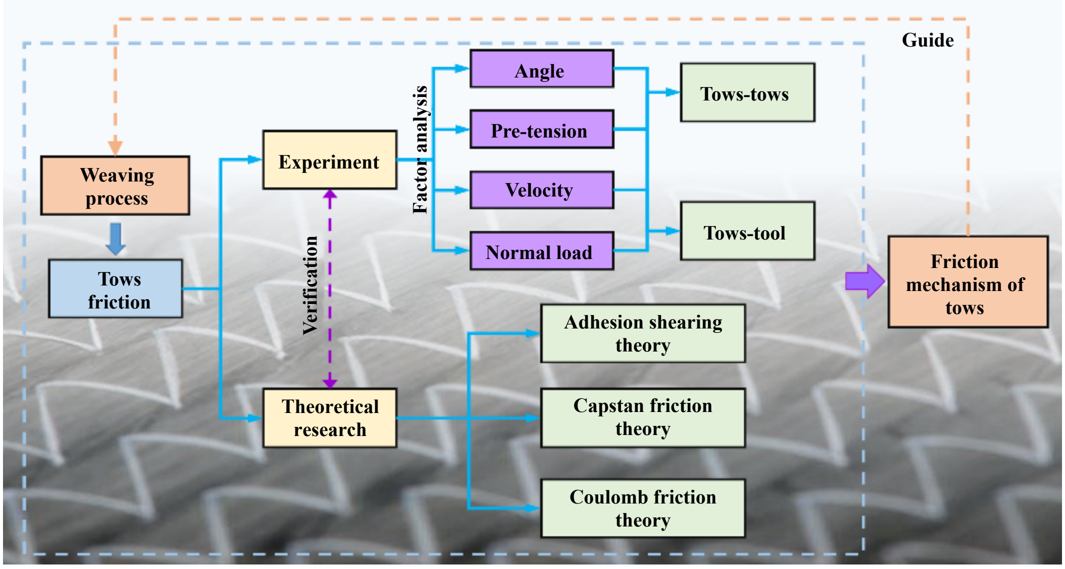

Fig. 2 Schematic of review route

图 2 综述路线示意图

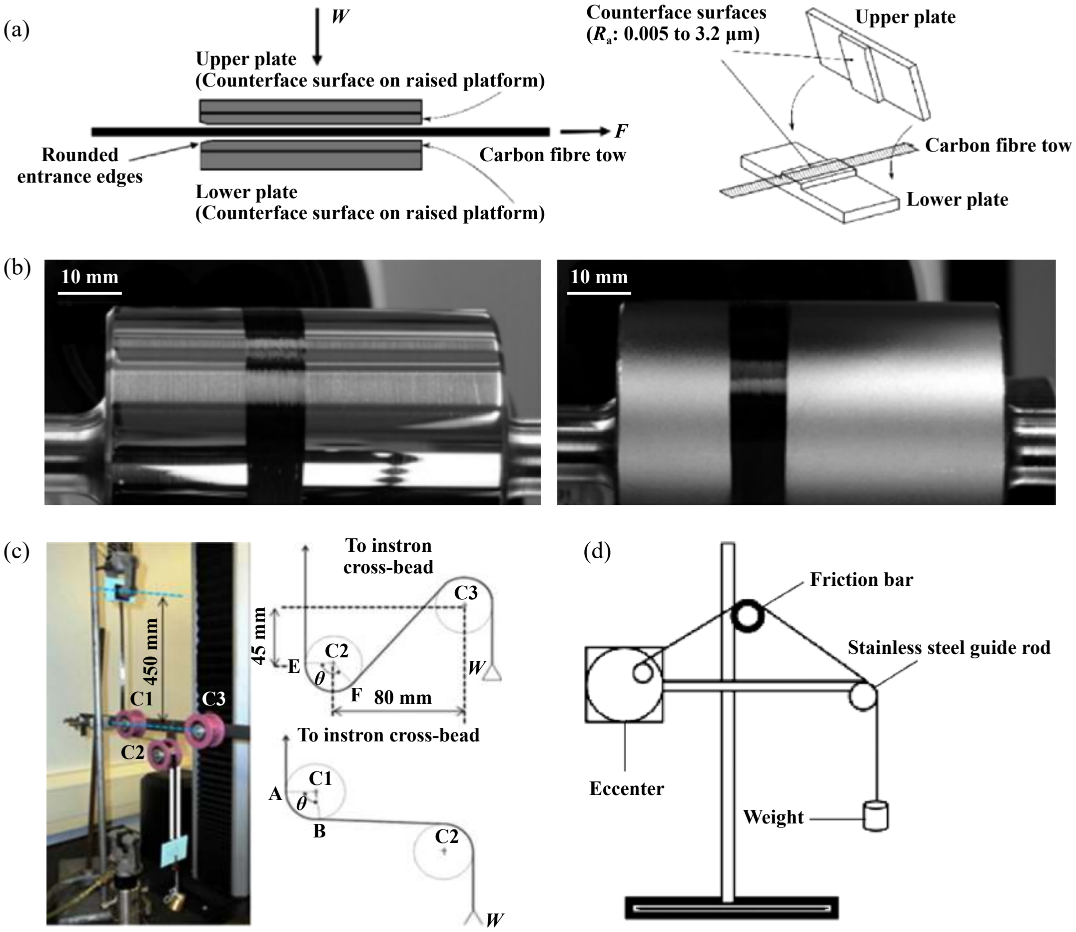

Fig. 3 (a) Schematic diagram of testing method for fiber frictional properties[37]; (b) capstan method for tows[43]; (c) wear-resistant device schematic[34]; (d) schematic of three angles of wrap[71]

图 3 (a)抽拔测试方法示意图[37]; (b)纤维束绞盘摩擦法[43]; (c)耐磨装置示意图[34]; (d)摩擦角示意图[71]

粗糙度变化的曲线. 研究发现，对于粗糙度小于0.1 μm的金属平板，随着表面粗糙度的减小，摩擦力迅速增加，但对于较大粗糙度的金属平板，摩擦力随粗糙度的变化并不显著. 李龙等[67]基于抽拔法原理，采用海

绵作为平板研究了东丽T800H和国产T800级碳纤维束磨损一段时间后毛丝量的变化规律，结果表明国产碳纤维毛丝量明显高于东丽碳纤维，国产碳纤维毛羽量随法向压力的增加先减小后增大，而东丽碳纤维毛丝量基本保持不变.

绞盘摩擦法是纤维束等柔软材料摩擦性能评价的另一种测试方法[68]. 如图3(b)所示，将样品悬挂于圆柱形摩擦辊上，纤维包覆角为φ，纤维束一端施加张力T_1，另一端连接载荷测试装置，载荷记为T_2，T_1-T_2即为摩擦力. Cornelissen等[43]设计了绞盘试验装置，讨论了与预制体成形相关的因素对纤维束摩擦性能的影响，结果表明，不同法向载荷导致接触面形貌发生变化，接触面形貌是影响纤维束-金属摩擦行为的主要因素，且摩擦力与法向载荷的变化趋势符合幂函数分布规律[69-70]. Abu Obaid等[24]基于绞盘摩擦法自制磨损试验机，对芳纶纤维束(KM2-600®)与两种玻璃纤维束(AGY S2®、Owens Corning Shield Strand S®)进行循环摩擦试验. 结果表明：表面浆料有助于提升纤维束耐磨性能，耐磨性能从优到差排序分别为芳纶纤维束(KM2-600)、玻璃纤维束(OCS Strand S)、玻璃纤维束(AGY S2). 绞盘摩擦方法不仅适用于细观尺度，还适用于微观尺度下纤维的摩擦测试. Wang等[33]采用高精度纳米摩擦试验机测试了超导NbTi材料和聚氯乙烯(PVC)在无润滑条件下的摩擦性能，结果与细观摩擦行为类似，纤维细度、法向负载和摩擦频率对摩擦性能均有显著影响.

随着绞盘摩擦方法的兴起，为了使之广泛适用于不同材料及条件的测试，研究人员基于绞盘摩擦原理设计了一些新型试验方法[72-74]. Chakladar等[34]使用如图3(c)所示的自制摩擦仪器对碳纤维束的摩擦行为进行了系统的试验研究，纤维束一端与载荷传感器连接，另一端绕过摩擦辊与砝码连接. Wu等[71]采用如图3(d)所示的摩擦磨损试验装置，研究了摩擦次数、法向负载和摩擦角度对碳纤维束摩擦磨损的影响. 上述研究表明，随着摩擦次数和法向负载的增大，碳纤维的磨损程度逐渐加剧，当摩擦角度在30°～90°范围内变化时，碳纤维的剩余拉伸断裂强力随着摩擦角度的减小而减小，当摩擦角度为0°时，剩余拉伸断裂强力急剧下降. 此外，众多研究人员考虑纤维性能[55, 67, 75-76]、纺纱工艺[77-78]、成形工艺[15, 79-82]及摩擦运动等参数[72, 82]建立了不同测试平台，进一步研究纤维束摩擦学特性.

1.2 纤维束-纤维束摩擦测试

在预制体成形过程中纤维束间受到外力作用发生变形，引起束间的相对滑动，按滑动方向可将纤维束-纤维束摩擦行为分为三种类型[83]，即长度-长度(l-l)方向、长度-半径(t-l)方向和半径-半径(t-t)方向，如图4(a)所示.

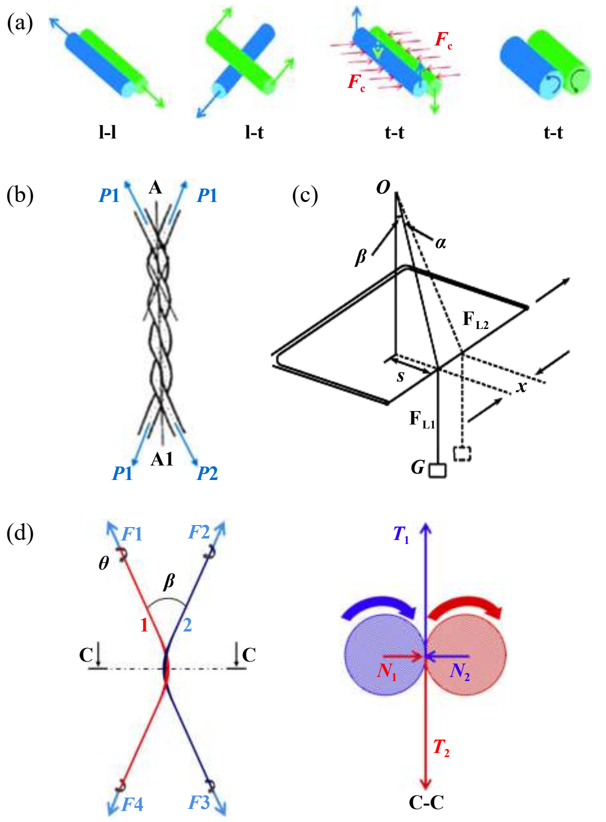

Fig. 4 (a) Classification of friction according to directions[60]; (b) l-l friction principle[34]; (c) l-t friction principle[84]; (d) t-t friction principle[60]

图4 (a)摩擦方式分类[60]；(b)l-l摩擦原理[34]；(c)l-t摩擦原理[84]；(d)t-t方向摩擦原理[60]

如文献[60]所述，研究人员为了评价纤维束的摩擦性能，基于长度-长度方向(l-l)摩擦测试原理设计了试验，两根绞合的纤维束的两端承受相同的预加张力P_1，如图4(b)所示. 在两根纤维束端部任意一处逐步施加连续拉力P_2 ($P_2>P_1$)，当P_2小于纤维束间最大静摩擦力与P_1总和时，束间螺旋接触面在相同结构下保持不动. 当P_2大于纤维束间最大静摩擦力与P_1总和时，束间螺旋接触面变化，发生滑动.

近年来，研究人员针对长度-半径方向摩擦原理(l-t)做了一系列研究. 如图4(c)所示，纤维束F_{L1}的一端固定于O点，另外一端跨过固定纤维束F_{L2}在重力G作用下自由悬挂. 当F_{L2}在水平方向上移动时，在摩擦力

作用下带动F_{L1}的自由端一起移动，直到F_{L1}自由端有滑动趋势，根据偏转角α、β及滑动距离x等变量可求解获得对应条件下的摩擦系数. Alirezazadeh等[35]基于此原理采用自行设计的高精度试验装置，研究了细度对聚丙烯纤维束摩擦行为的影响，结果表明，由于细度不同导致接触形状各异，纤维束的摩擦行为受接触面几何形状的影响较为严重. Abdellahi等[36]采用有限元的方法对图4(c)所示的测试方式进行了数值模拟，发现计算结果与试验结果吻合较好，最大误差在4.3%左右. 依照l-t摩擦原理的测试方法结构简单且使用方便，但无法有效控制纤维束预加张力和法向负载等条件，进而导致摩擦过程波动明显，精度较低. 随着高精度传感器的出现，研究人员在原有设备的基础上设计出变量可控且波动较小的试验装置. Tourlonias等[52]通过NTR2纳米摩擦仪对两根垂直纤维束间的摩擦行为进行试验，研究了不同牌号碳纤维束的摩擦频率和法向载荷对其摩擦性能的影响. 结果表明，纤维束的摩擦行为遵循Coulomb定律，摩擦频率与法向载荷对纤维束摩擦系数的影响不显著.

除了长度-长度(l-l)和长度-半径(l-t)方向的摩擦原理外，根据半径-半径(t-t)方向摩擦原理进行纤维束摩擦学特性研究也尤为重要，例如在T300-12K和T800-6K等牌号碳纤维束内存在t-t方向的摩擦行为，在织物内部存在纤维束间的t-t方向摩擦行为. t-t方向摩擦行为在预制体成形过程中十分重要，但是依照t-t原理的摩擦研究并不常见. Shanwan等[60]设计了如图4(d)所示的摩擦试验装置，两根承受相同拉力的纤维束呈β交织，以角速度θ转动纤维束. 在旋转运动中，产生两类扭矩：由于旋转运动而传递到纤维束间接触区的弹性扭矩和由纤维束间切向摩擦力T_1、T_2引起的阻性扭矩. 当弹性扭矩在旋转中占主导时，两根交织的纤维束之间将发生滑动，即t-t方向的摩擦行为.

2　纤维束摩擦学特性影响因素分析

通过摩擦测试可以有效表征预制体成形过程中纤维束的摩擦性能，研究人员开展了大量的参数化研究，基于纤维束摩擦后的剩余断裂强力，探讨了各因素对纤维束摩擦性能的影响规律，并分析其摩擦磨损机理[85].

2.1　纤维束摩擦角度

在预制体成形过程中，纤维束受到不同角度条件下的摩擦磨损，尤其是在3D预制体成形过程中愈发明显，纤维束-纤维束摩擦测试中，摩擦角度指纤维束间所夹锐角，可通过调节纤维的初始位置进行改变. 根据之前纤维束-纤维束摩擦研究可发现[44, 51-52, 86]，随着摩擦角度的逐渐减小，接触面积增大，纤维束摩擦行为加剧，磨损严重. 焦亚男等[86]采用图5(a~b)所示夹具研究了摩擦角度对石英纤维束摩擦性能的影

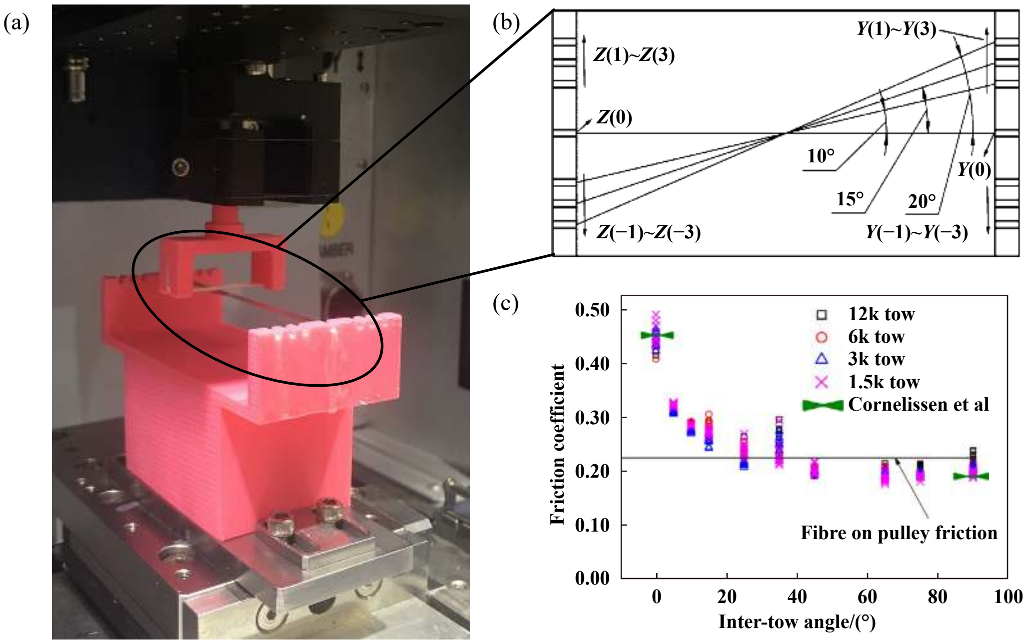

Fig. 5　(a) Fixture on machine[86]; (b) schematic diagram of key dimensions of lower fixture[86]; (c) effects of inter-tow angle on tow friction[34]

图 5　(a)自制夹具上机图[86]; (b)下夹具主要尺寸示意图[86]; (c)摩擦角度对纤维束摩擦行为的影响[34]

响，结果表明随着摩擦角度的减小，纤维束间的接触面积逐渐增大[38]，导致纤维束间的摩擦阻力增大，摩擦后纤维束表面断纤维(毛羽)增多，即纤维磨损严重. Chakladar等[34]采用试验与仿真方法从细观尺度对碳纤维束的摩擦行为进行了研究，发现纤维束间摩擦角度减小，会引起纤维束接触区域增大，牵引力方向变化，造成沿摩擦方向分力增大，进而导致摩擦系数增大，磨损严重. 此外，Chakladar[34]还发现纤维束间发生摩擦时会出现纤维迁移和缠结等现象，并且得到摩擦角度为0°时的摩擦系数是90°时的两倍的结论[图5(c)]. 纤维束在预制体成形过程中受到不同角度的摩擦，导致接触行为变化复杂，因此预制体成形过程中应以解决由纤维束取向造成的摩擦损伤为主，从而降低最终成型的复合材料制品力学性能和使用寿命损失.

针对纤维束-金属的摩擦行为，摩擦角度指纤维束与金属接触后自由端之间的夹角. 潘月秀等[71]对摩擦后碳纤维束的拉伸性能进行了分析，结果表明当纤维束之间的夹角为30°~90°时，随着夹角的减小，碳纤维束的剩余拉伸断裂强力虽然呈下降趋势，但变化并不显著. 当夹角为0°时，碳纤维束的拉伸断裂强力骤降，与原样相比下降了84.90%，这是由于随着夹角的减小，位于上层的碳纤维束与下层摩擦辊表面的碳纤维束逐渐重合，且碳纤维束形貌为扁平带状，在预加张力的作用下处于伸直状态，因此随着夹角的减小，上下层碳纤维束接触区域的部分轮廓面积不同. 从细观角度分析可得，随着摩擦角度的减小，纤维束磨损严重[38]，这是由于随着纤维束间接触面积的增大，纤维束间的摩擦阻力增大，进而导致摩擦后纤维束表面断纤维较多，磨损剧烈.

2.2 纤维束摩擦频率

纤维束摩擦频率指纤维束-金属或纤维束-纤维束在单位时间内发生摩擦行为的次数，是描述摩擦行为快慢的物理量，单位为Hz. 既往研究表明，摩擦频率仅影响达到摩擦稳定的时间，对摩擦行为没有明显影响. 杨洁等[62]采用图6(a)所示的夹具研究了摩擦频率对纤维束间摩擦行为的影响，发现摩擦频率变化不会影响碳纤维束的摩擦力F_f和摩擦系数μ [图6(b)]，但延长了其达到稳定所需的周期数. 这是因为碳纤维在5 Hz摩擦时动能大，导致碳纤维束在正交往复运动过程中所受到的沿摩擦滑动方向作用力增加，进而束内纤维重新排列形成稳定摩擦界面层所需的“磨合”周期数增加. 焦亚男等[86]设计了一种纤维束摩擦磨损试验夹具，使纤维束或纤维能够呈一定角度接触，从准纤维尺度上研究了摩擦频率对纤维束间摩擦行为的影响. 结果表明，随着摩擦频率的增加，单位时间内摩擦次数增加，纤维重排达到稳定状态的时间更短，但总摩

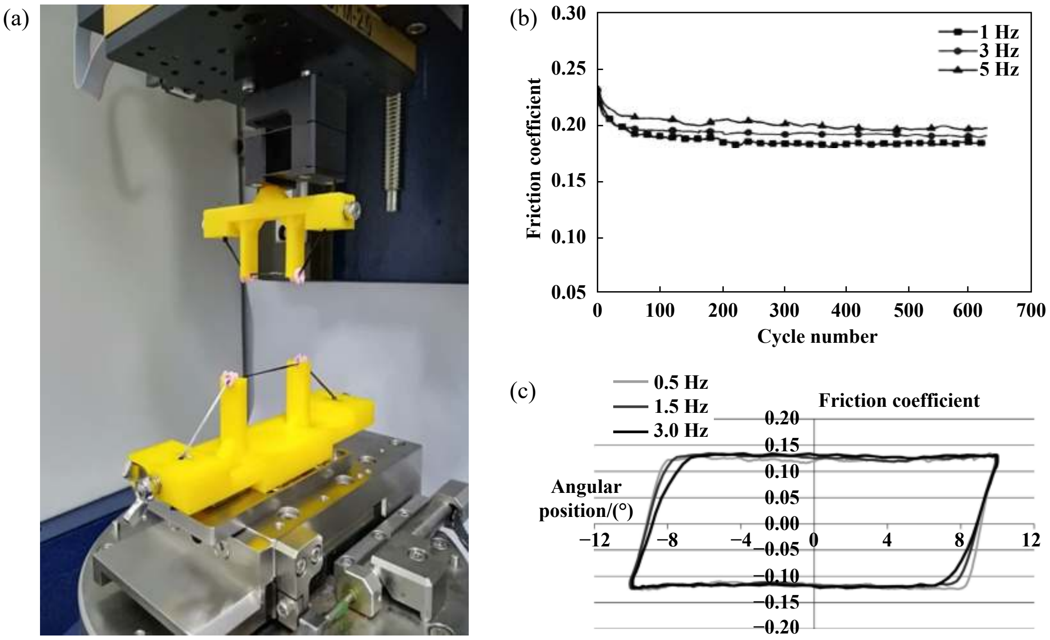

Fig. 6 (a) Figure of the upper and lower fixture[62] (b) average cyclic curve of friction coefficient versus angular position for SM single fibre friction with different oscillation frequencies[52] (c) effect of friction velocity on friction coefficient of carbon tows[63]

图6 (a)上下夹具装置示意图[62]；(b)不同摩擦频率条件下SM纤维摩擦系数与角位置的关系曲线[52]；(c)摩擦频率对碳纤维束摩擦系数的影响[63]

擦次数未变，再次证明摩擦频率对摩擦行为没有明显的影响. 其他学者从摩擦能的角度得到了相同的结论，Tourlonias等[44]模拟了不同织造频率条件下经纱的摩擦行为，采用摩擦能作为束间摩擦磨损性能的量化指标. 结果表明：1.5、3.0和4.0 Hz三种频率对摩擦系数与摩擦消耗的能量无明显影响. 此外，Tourlonias等[52]进一步以纤维为研究对象进行试验，得出图6(c)所示结论，三种摩擦频率条件下摩擦系数与角位移间的变化规律一致.

2.3　纤维束预加张力

预加张力作为复合材料成型过程中的关键变量，将导致复合材料制品的力学性能损失甚至失效. 研究预加张力对纤维束-纤维束摩擦磨损的影响规律，对预制体成形工艺的优化具有重要意义. 图7(a)所示为Ismail等[87]用于研究预加张力对纤维束间摩擦性能影响的试验装置，结果表明，随着预加张力的增大，摩擦系数呈减小趋势. 由于该研究的重点是试验装置及测试方法，并未对预加张力进行细致探讨. Ismail等[53]采用新的表征方法并对比理论模型进一步对该问题进行探讨，结果如图7(b)所示，摩擦力随预加张力的增加而逐渐减小. 这是由于增大预加张力使纤维束间的接触长度减小，进而导致接触尺寸和摩擦力减小.

在纤维束与金属的摩擦测试中，通常采用悬挂砝码的方法赋予纤维束预加张力. 杨洁等[63]自制张力可控的摩擦试验夹具搭配UMT-TriboLab摩擦磨损试验机进行碳纤维束-筘齿的摩擦试验. 根据实际织造过程中纤维束受到的预加张力确定试验参数，研究了预加张力为0.5、0.7和0.9 N时对碳纤维束-筘齿摩擦性能的影响，发现在不同预加张力下，纤维束的摩擦力与摩擦系数的数值大小差异不明显，这说明试验所选择的预加张力范围对纤维束与筘齿的摩擦行为影响较小. 在绞盘摩擦方法中，预加张力由纤维束自由端施加的外力所决定，称为输入张力.

2.4　纤维束法向载荷

为研究初始法向载荷对摩擦力F_f和摩擦系数的影响，在摩擦频率为0.5 Hz条件下，Tourlonias等[44, 88]开展了法向载荷为200、500和800 mN时的束间摩擦磨损试验研究. 结果如图8(a)所示，在法向载荷较小的条件下，摩擦行为稳定，分析认为可以用黏附接触理论解释该现象，但文中并未进行深入探讨. Wu等[50]采用图8(b)所示的夹具研究了法向载荷对纤维束-金属摩擦磨损性能的影响. 结果表明摩擦力与法向载荷(N_{tow})遵循幂函数规律，即$F = N_{\mathrm{tow}}^{0.734}$，与Tourlonias等所得结论类似，分析认为接触面积作为法向载荷影响纤维束摩擦性能的关键变量，通过计算实际和理论接触接触面积，发现法向载荷与接触面积呈幂函数关系，且指数差为0.004. 因此，文中所提的幂函数可较好地反映法向载荷与摩擦力之间的关系.

法向载荷对摩擦行为的影响机制不仅适用于微米级纤维，而且在纳米级纤维的摩擦研究中也十分常见，Ismail等[53]为了研究法向载荷对摩擦行为的影响，绘制了1~10 mN范围内摩擦力的变化趋势图，其结果与Tourlonias等[52]的结论一致，即法向载荷与摩擦力呈正比例关系. Wang等[33]研究了法向载荷对不同直径NbTi微细纤维动摩擦系数的影响，并根据Howell绞盘摩擦理论[84]，当纤维受到更大的法向载荷时，其在摩擦时接触面积越大，摩擦力越大.

3　纤维束摩擦行为力学模型

纤维束摩擦磨损涉及到纵向拉伸、横向压缩和弯曲等多种变形和损伤过程，建立摩擦过程的力学分析模型是研究纤维束摩擦行为的重要手段. 本节中将对

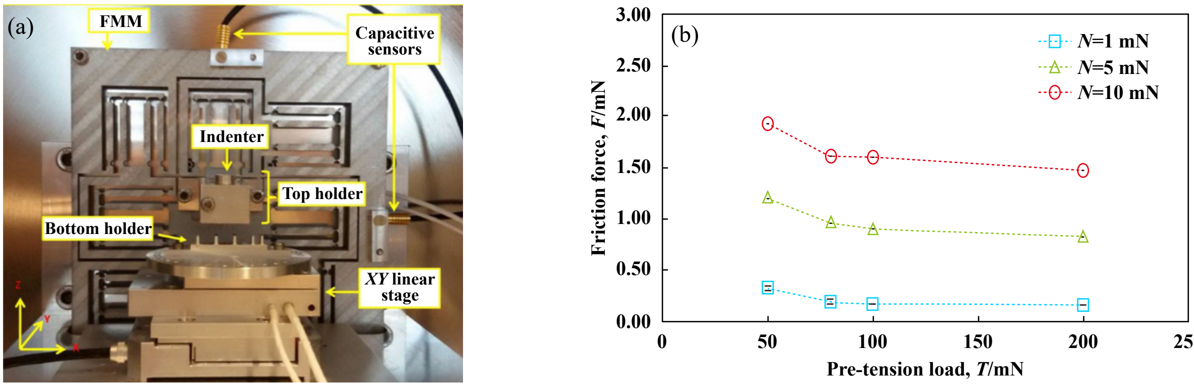

Fig. 7　(a) Schematic description of friction experiment between fibres[53]; (b) friction force as a function of pre-tension load[53]

图 7　(a)摩擦实验装置示意图[53]; (b)摩擦力与预拉伸载荷的关系[53]

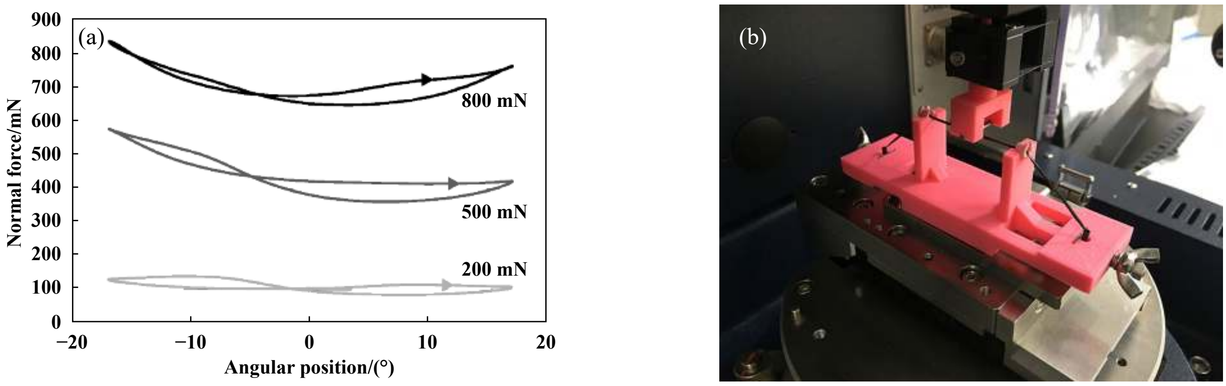

Fig. 8 (a) Influence of the normal load on the average cycle in terms of normal force[44]; (b) photograph of experimental rig mounted on friction tester[63]

图 8 (a)法向载荷与角位置的关系曲线[44]; (b)摩擦试验装置照片[63]

纤维束摩擦磨损行为的力学分析模型进行总结.

3.1 绞盘摩擦模型

在ASTM D3108/D3412中将绞盘摩擦模型作为纤维束与圆辊摩擦的分析模型. 为克服纤维束绕过绞盘后受到的摩擦阻力，输出张力T+dT须大于另一端输入张力T，纤维束张力引起的法向力N的变化由式(1)表示[72].

$$\mathrm{d}N = T\sin\left(\frac{\mathrm{d}\theta}{2}\right) + (T+\mathrm{d}T)\sin\left(\frac{\mathrm{d}\theta}{2}\right) \tag{1}$$

由于dθ很小，sin(dθ/2)可用dθ近似表示，并且忽略了高次项，此外，摩擦是拉力T增大的主要原因，即

$$\begin{cases}\mathrm{d}N = T\mathrm{d}\theta \\ \mathrm{d}T = \mu T\mathrm{d}\theta\end{cases} \tag{2}$$

令T=T_1，T+dT=T_2，得到绞盘方程：

$$\int_{T_1}^{T_2}\frac{\mathrm{d}T}{T} = \int_0^{\theta}\mu\mathrm{d}\theta \tag{3}$$

求解上述方程得到绞盘方程：

$$T_2 = T_1\mathrm{e}^{\mu\theta} \tag{4}$$

其中：θ是缠绕角度；T_1为输入张力，T_2为输出张力.

研究人员[59]基于绞盘法设计了一种用于测量纤维束摩擦系数的方法，即绞线法，通过式(5)可算出纤维束的摩擦系数μ_{app}.

$$\mu_{\mathrm{app}} = \ln\left(\frac{T_2}{T_1}\right)\frac{1}{2\pi n\alpha} \tag{5}$$

其中：n为纤维束的捻度，α为纤维束间夹角.

绞盘摩擦模型对绞盘法和绞线法中纤维的受力情况进行了分析，较好地解释了测试过程中纤维\纤维束的力学行为，在此基础上，研究人员为适应不同测试要求，对试验装置进行了改进[42]，相继开发了纱线摩擦测试仪、R-1 182型直读式电子摩擦系数测试仪和LYF-19型纱线动态摩擦系数测试仪. 绞盘方程也被称为欧拉方程，本质上通过牛顿第二运动定律计算，但惯性张量的各分量受环境影响明显，因此模型适用范围有限[89].

3.2 Coulomb摩擦模型

Coulomb摩擦模型作为描述摩擦副间摩擦行为的重要模型，是许多摩擦测试方法依照的基本模型[79-80]，如式(6)所示.

$$\mu = \frac{F_{\mathrm{f}}}{N} \tag{6}$$

其中：μ为摩擦系数，N为法向载荷.

在该模型的基础上，研究人员做了许多相关工作，Howell[84]提出的摩擦力与法向载荷之间的非线性数学模型在描述纤维集合体的摩擦行为方面得到了广泛的认可，Rao等[90]基于Howell的研究建立了适用于纤维束/纤维的摩擦模型，如式(7)所示.

$$F_{\mathrm{f}} = aN^{n} \tag{7}$$

其中：F_{f}为摩擦力，a和n通常为模型常数. 系数a通常取决于样品的物理、化学特性以及形态特征. 指数n通常取决于材料特性和变形机理[91]，取值范围为2/3~1；当材料发生完全弹性变形时，n为2/3；当材料发生完全塑性变形时，n为1.

3.3 黏附摩擦模型

Bowden和Tabor等[92]研究了纤维的摩擦行为，发现摩擦力主要包括剪切力与犁沟力两部分[93]，如式(8)所示.

$$F_{\mathrm{f}} = A_{\mathrm{r}}\tau + P \tag{8}$$

其中：F_{f}为摩擦力；A_{r}为纤维束实际接触面积；τ为界面剪切强度；P为犁沟力.

上述摩擦模型适用于纤维束-纤维束和纤维束-金属摩擦，虽然纤维模型由两部分组成，但由塑性变形造成的犁沟力在实际纤维摩擦行为中几乎不影响摩擦力，因此实际可忽略P的作用[39]，即

$$F_{\mathrm{f}} = A_{\mathrm{r}} \cdot \tau \tag{9}$$

在忽略P的作用后，即可认为纤维之间是光滑接触，根据Hertz接触理论[23]，纤维实际接触面积A_{r}可表示为

$$A_{\mathrm{r}} = \pi \left(\frac{3F_{\mathrm{N}}R}{4E^{*}} \right)^{\frac{2}{3}} \tag{10}$$

其中：F_{N}为法向载荷，R为等效半径，E^{*}为等效模量，表示为

$$\frac{1}{E^{*}} = \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2} \tag{11}$$

其中：E_1和E_2为摩擦副的弹性模量；v_1和v_2为摩擦副的泊松比[94-95].

由于接触后纤维横截面由圆形变为椭圆形，因此等效半径R表示为

$$\begin{cases} R = \dfrac{1}{R'} + \dfrac{1}{R''} & \theta = 0 \\ R = \left(\dfrac{1}{R'^2} + \dfrac{1}{R''^2} + \dfrac{2}{R'^2 R''^2} \cdot \cos(2\theta) \right)^{\frac{1}{2}} & \theta \neq 0 \end{cases} \tag{12}$$

其中：R'和R''分别为两接触物体的曲率半径；θ为纤维中心轴之间的夹角.

Tourlonias等将纤维束实际接触面积表示为

$$\begin{cases} A_{\mathrm{r/tow}} = 2nA_{\mathrm{r}} & \theta = 0 \\ A_{\mathrm{r/tow}} = n^2 A_{\mathrm{r}} & \theta \neq 0 \end{cases} \tag{13}$$

其中n为纤维束中的纤维根数，通过式(14)计算得到：

$$n = \frac{W}{d} \tag{14}$$

其中：W为纤维束宽度，d为纤维直径.

Tourlonias等[52]在计算纤维束中纤维根数时，未考虑纤维重新排列的影响，为详细地解释黏附摩擦理论，Mulvihill等[23]在考虑接触角度θ的基础上研究了纤维束的摩擦行为，结果表明黏附摩擦理论不能解释所涉及的全部摩擦机理，这是由于纤维在不同接触条件下相互滑移，重新排列组合形成新的接触面. 该模型对于束内纤维的排列状况依然延续了前人的假设，并未将纤维的排列规律完整表述，在多次摩擦循环后，纤维束受到挤压，导致纤维束间的纤维接触层相互渗透，实际接触面积改变，理论摩擦力计算存在偏差[96]. 因此，黏附摩擦模型对准确描述纤维束摩擦行为还存在局限性，仅适用于束内纤维取向度低、平行顺直排列的纤维束，对具有捻度或合股纤维束的摩擦行为分析还有待改善.

4　结束语

本文中对纺织复合材料预制体成形过程中纤维束摩擦磨损行为展开论述. 从测试方法、影响因素和理论分析模型等方面进行了归纳. 概述了纤维束-金属和纤维束-纤维束摩擦测试方法的优缺点；分析得出了摩擦角度、摩擦频率、预加张力和法向载荷对纤维束摩擦性能的影响机制；进一步总结了纤维束摩擦磨损行为的理论分析模型. 目前，人们对纺织复合材料预制体成形过程中的纤维束摩擦行为研究已取得了实质性进展，对今后的纺织工艺设计和预制体纤维束摩擦损伤分析具有指导意义，但该领域的研究仍存在一些关键问题亟待解决.

a. 目前针对纤维束的摩擦学性能研究多集中于纤维束的摩擦测试方法、磨损表征和耐磨性能改善等方面，对复杂结构预制体成形过程中纤维束的接触、挤压变形和摩擦磨损机理方面的研究还不够深入. 因此，需要将纺织成形工艺与上述机理联系起来，对复杂力学条件下纤维束的摩擦行为进行系统分析.

b. 本文中仅对纤维束摩擦性能的4个主要影响因素开展了综述，但预制体实际成形过程中还存在许多其他不易表征的微细观因素，如纤维表面浆膜的黏附作用、纤维束的取向度和排列规律等. 因此，有必要建立精细化仿真模型，结合试验手段对纤维束摩擦磨损特性进行多尺度、参数化研究.

c. 根据摩擦行为力学模型可知，纤维束摩擦磨损是复杂力学条件下的多因素耦合作用结果. 以往的研究主要以探索单因素对摩擦行为的影响为主，多因素耦合作用对摩擦行为影响的研究却十分少见，现有测试方法尚不能完整、准确地反映纤维束的实际受力情况. 因此，动态摩擦行为监测与多因素耦合分析是深入开展纤维束摩擦磨损特性研究的关键.

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