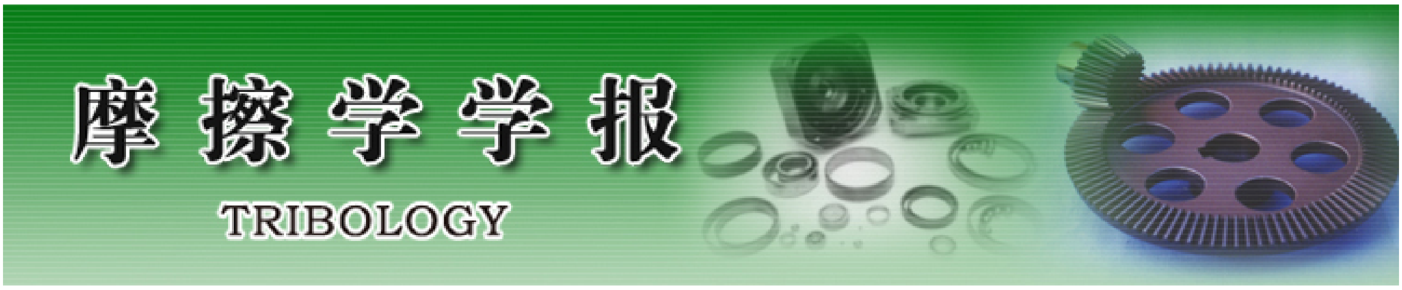

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温度对PTFE/Kevlar织物复合材料摩擦磨损性能的影响

李伟博[1,2], 刘　建[1,2*], 赵宁波[1,2], 郑晓猛[1,2], 杜三明[1,2], 上官宝[1,2], 张永振[1,2]

(1. 河南科技大学 高端轴承摩擦学技术与应用国家地方联合工程实验室, 河南 洛阳 471023;
2. 河南科技大学 材料科学与工程学院, 河南 洛阳 471023)

摘　要: 为了探究不同温度下复合材料摩擦系数、磨损率的转变以及材料摩擦磨损行为和损伤机制的演变规律，将制备的PTFE/Kevlar织物复合材料，在不同温度(25~150 ℃)、载荷(20~40 MPa)和频率(6~10 Hz)下进行往复式摩擦磨损试验. 试验结果表明：载荷与频率对复合材料摩擦磨损性能的影响远小于环境温度，随着环境温度的升高，摩擦系数和磨损率呈现先减小后增大的趋势，温度为75 ℃时材料的摩擦系数和磨损率最小. 当环境温度、载荷和频率分别为75 ℃、30 MPa和6 Hz时，复合材料的摩擦系数约为0.039，磨损率约为5.98×10^{-15} $m^3/(N\cdot m)$. 随着温度升高至100 ℃以上，材料摩擦系数和磨损率急剧增大且摩擦系数出现剧烈波动. 使用扫描电镜(SEM)和X射线能谱(EDS)对复合材料、转移膜和磨屑进行深入分析发现，复合材料的磨损行为与PTFE纤维的断裂行为有关. 随着环境温度的逐渐升高，PTFE纤维断裂行为由滑动剪切挤出逐渐转变为纤维拔出、切断和疲劳剥落. 复合材料的磨损机制，由磨粒磨损转变为轻微黏着磨损，再转变为严重的黏着磨损并伴随着热复合型的疲劳磨损.

关键词: 织物复合材料; 温度; 树脂; 转移膜; 摩擦磨损
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The Effect of Temperature on the Friction and Wear Properties of PTFE/Kevlar Fabric Composites

LI Weibo[1,2], LIU Jian[1,2*], ZHAO Ningbo[1,2], ZHENG Xiaomeng[1,2],
DU Sanming[1,2], SHANG GUAN Bao[1,2], ZHANG Yongzhen[1,2]

(*1. National United Engineering Laboratory for Advanced Bearing Tribology, Henan University of Science and Technology, Henan Luoyang 471023, China;*
2. School of Materials Science and Engineering, Henan University of Science and Technology, Henan Luoyang 471023, China)

Abstract: Self-lubricating fabric composites are the key materials in self-lubricating joint bearings, however, during the friction process, high temperature and high speed working conditions, the large accumulation of frictional heat leads to a significant decrease in the overall stability of the composites. It is of great significance to explore the transformation of friction coefficient and wear rate of composites under different temperatures and the evolution of material friction and

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*Corresponding author. E-mail: lixinliu@haust.edu.cn, Tel: +86-18338808659.
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wear behavior and damage mechanism to improve the self-lubricating performance and wear life of spherical plain bearings. In this paper, the prepared PTFE (Polytetrafluoroethylene)/Kevlar fabric composites were subjected to reciprocating friction and wear tests at different temperatures (25~150 ℃), loads (20~40 MPa), and frequencies (6~10 Hz) by using a heavy-duty reciprocating friction and wear tester. The test results showed that the change of load and frequency had much less effect on the composites than the temperature. The change of frequency could be defined as the change of friction temperature. At 25 ℃, the friction coefficient and wear rate of the material decreased gradually with the increase of frequency from 6~10 Hz. As the load increased from 20 MPa to 40 MPa, the friction coefficient and wear rate of the material first decreased and then increased. However, when the temperature started to act, as the temperature increased from 25 ℃ to 150 ℃, the friction coefficient and wear rate of the composite material showed a tendency of decreasing and then increasing under the influence of temperature. When the temperature was 75 ℃, the composites showed excellent friction and wear performance, and their friction coefficient and wear rate reached the minimum value. When the ambient temperature, load and frequency were 75 ℃, 30 MPa and 6 Hz, the friction coefficient of the composite material was about 0.039 and the wear rate was about 5.98×10^{-15} $m^3/(N\cdot m)$. As the temperature increased above 100 ℃, the material friction coefficient and wear rate increased dramatically and the friction coefficient fluctuated drastically, and the mean value of the friction coefficient was as high as 0.117 and the standard deviation was as high as 0.024 5 at 150 ℃. In-depth analyses of the composites' wear surfaces, transfer films, and abrasive debris using scanning electron microscopy (SEM) and X-ray spectroscopy (EDS) revealed that the wear behaviors of the composites were related to the fracture behavior of PTFE fibers. As the temperature increased from 25 ℃ to 150 ℃, the PTFE fiber fracture behavior gradually changed from sliding shear extrusion to fiber pulling out, cutting off, and fatigue spalling. 75 ℃, the PTFE fiber plastic flow phenomenon was extremely obvious, and the wear surface of the F element content accounted for as high as 34.2%. At this time, the friction process formed in the abrasive debris presented a fine block form, and the transfer film formed on the surface of the dyadic pin uniformity and stability was better, so at this time the material's friction coefficient fluctuation was more stable, the standard deviation of the standard deviation was low to 0.005 3. Correspondingly, with the temperature increased from 25 ℃ to 150 ℃, the composite material of the abrasive wear mechanism, from abrasive wear into a slight adhesive wear, and then transformed into a serious adhesive wear. wear and accompanied by thermal composite fatigue wear. In order to ensure the wear resistance of self-lubricating materials, the friction temperature of 50~75 ℃ could make the composites maintain in the stage of slight adhesive wear for a long time.

Key words: fabric composites; temperature; resin; transfer film; friction and wear

自润滑关节轴承主要由内圈、外圈和自润滑衬垫材料组成，因其结构紧凑、承载能力强和免维护等优点，被广泛应用于航空航天以及精密机械等高端装备领域[1-3]. PTFE纤维织物作为自润滑衬垫材料的1种，常用PTFE纤维与容易粘接的Kevlar纤维混合编织成薄层织物与酚醛树脂复合而成. 使得织物兼具PTFE的高润滑性能和Kevlar的优良力学性能[4-5]. 然而在摩擦过程中，高温和高速工况条件，摩擦热的大量累积，导致复合材料的整体稳定性大幅下降[6-8]. 因此，研究温度对复合材料磨损机制和行为的影响，对提高球面滑动轴承的自润滑性能和磨损寿命具有重要意义. Wang等[9]通过研究发现摩擦温度的升高导致PTFE复合材料之间的黏着磨损. 齐慧敏等[10]开展了宽温域范围内的摩擦磨损试验，结果表明摩擦过程中PTFE转移至对偶表面，发生摩擦氧化及螯合反应，显著影响了摩擦膜的形成. 为了提高织物复合材料的热稳定性，研究人员通过表面改性技术提高纤维机械互锁和化学结合来增强界面黏附性[11-13]. 微量填料的掺入使聚合物复合材料具有更好的力学和摩擦学性能[14]. 赵鑫等[15]将改性玄武岩颗粒和氟化石墨构成的二元复合填料引入PTFE/Nomex混纺织物，极大增强了复合材料的抗磨性能和热稳定性能. 王壮等[16]在PTFE基体中添加CaF_2微米颗粒明显提高了PTFE的耐磨性能. 除温度外，复合材料的摩擦学性能还受到载荷和速度的影响. 负载会造成树脂的应力集中，导致纤维的挤压和断裂[17-20]. 速度会产生摩擦热的快速积累，造成树脂的软化，使得树脂基体的承载能力大幅下降，纤维被大量挤出，从而造成剧烈磨损[21].

由于芳纶纤维对PTFE和树脂的容纳性良好，一般采用斜纹或缎纹的编织形式对两者进行混编，得到摩擦磨损性能优异的织物复合材料[22-24]. 为了研究温度对高速重载条件下复合材料摩擦磨损性能的影响，本试验中将制备的PTFE/Kevlar斜纹织物复合材料进行不同温度下的摩擦磨损试验. 试验表明，在75 ℃条

件下，织物复合材料表现出最好的摩擦学性能. 随着温度的升高，磨损机制由磨粒磨损转变为黏着磨损，复合材料的磨损行为主要与PTFE纤维的断裂形式有关. 揭示不同温度条件下磨损机制的转变，对提高织物复合材料的摩擦学性能、材料改性提供理论参考.

1　试验部分

1.1　材料制备

PTFE/Kevlar纤维织物复合材料由PTFE纤维(细度：400 D)和Kevlar纤维(细度：200 D)混合编织(斜纹结构，织物厚度0.38±0.02 mm，面密度1.45 g/m^3)，用于增强的Kevlar纤维采购于美国杜邦公司. 织物粘接剂为有机硅改性酚醛树脂，由上海新光树脂厂提供. 粘接前将织物浸泡在丙酮试剂中12 h，之后将织物浸泡在树脂中，使用超声仪器震荡并搅拌，去除气泡. 将处理过的织物放置到热滚压机中，进行预固化，预固化过的复合材料如图1所示. 将固化过的织物粘接面均匀涂抹树脂与GCr15基底相结合，放置真空热压机中，在180 ℃和0.8 MPa条件下热压2 h. 试样剥离强度为0.33~0.36 N/m. 以上制备过程均在中科院兰州化学物理研究所进行. 试验中对偶件采用直径5 mm和长度60 mm的GCr15圆柱体钢销，表面粗糙度为0.16 μm，硬度为62HRC，将销底部倒半径为1 mm的圆角.

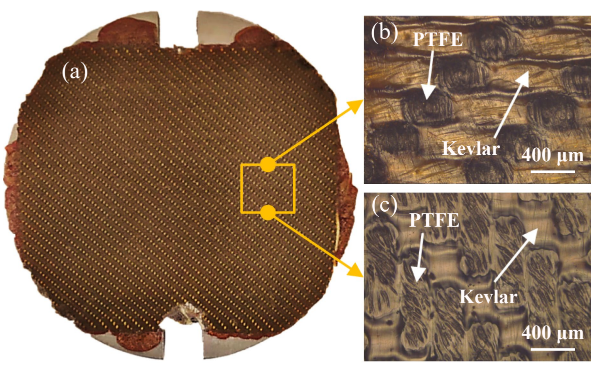


Fig. 1　PTFE/Kevlar fiber woven composite: (a) sample; (b) bonding surface; (c) wear surface
图 1　PTFE/Kevlar纤维编织复合材料：(a)样品；(b)粘接面；(c)磨损表面

1.2　试验方法

使用HL-R7000重载往复摩擦磨损试验仪，如图2所示，对PTFE/Kevlar织物复合材料进行摩擦磨损试验. 该试验仪采用销盘式结构，使用夹持装置将GCr15圆柱体钢销固定，加载装置施加载荷，通过偏心轮的转动实现往复运动，往复距离6 mm. 在本研究中，滑动方向始终与PTFE纤维束垂直. 通过往复装置

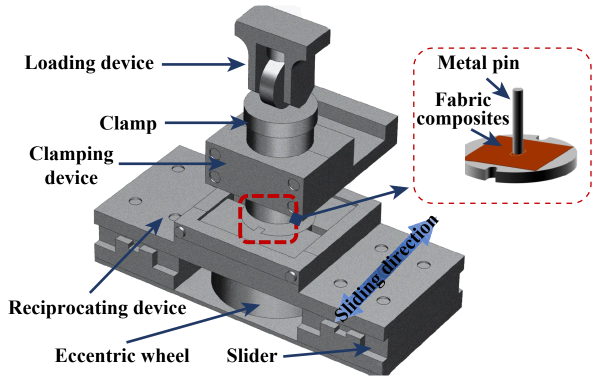


Fig. 2　Heavy duty reciprocating friction and wear tester
图 2　重载往复摩擦磨损试验仪

底部的加热装置与热电偶的协同作用，达到试验过程中所需温度条件.

本研究中，根据杨育林等[25]开展的不同环境温度下的摩擦磨损试验以及自润滑织物复合材料的常用工况条件. 本试验选取温度(25、50、75、100和150 ℃)、载荷(20、30和40 MPa)以及频率(6、8和10 Hz)为试验参数，对材料进行每组10 h的摩擦磨损试验. 每次测试前，摩擦面用丙酮试剂进行擦拭. 试验过程中实时监测记录摩擦系数. 每次试验结束时，使用EC-770S涂镀层测厚仪测量材料的厚度，计算出磨损体积，根据磨损体积得出每组试验的磨损率数据. 为保证试验的可重复性和可靠性，试验均重复5次，取平均值. 使用JSM-IT100型扫描电子显微镜(SEM)对摩擦面和磨屑进行表征，X射线能谱仪(Xplore)进行表面元素分析.

2　结果与讨论

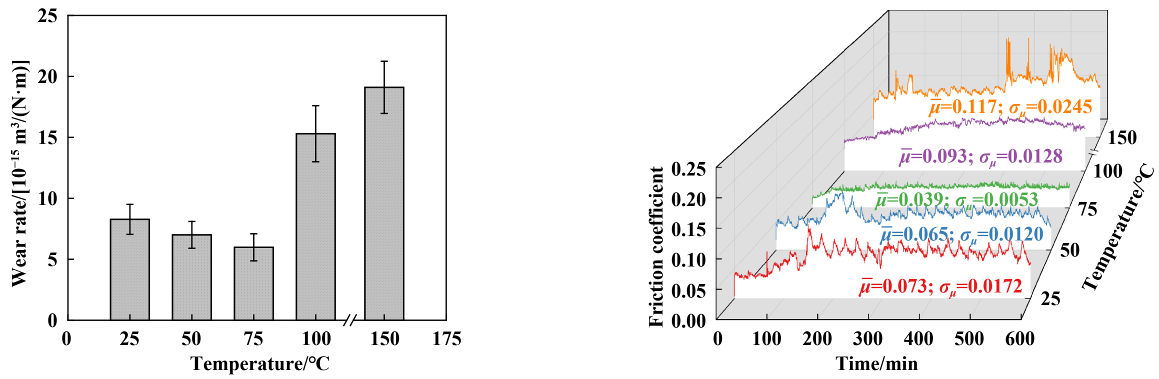
2.1　摩擦磨损试验

图3所示为不同温度下的摩擦系数和磨损率. 复合材料摩擦系数和磨损率随着温度的升高，先降低后升高. 25 ℃时，摩擦系数均值为0.073，标准差为0.017 2. 当温度达到75 ℃时，摩擦系数和磨损率达到最小值，分别为0.039和5.98×10^{-15} m^3/(N·m)，摩擦系数波动较为稳定，标准差为0.005 3. 在温度升高至100 ℃后，摩擦系数明显增大且剧烈波动. 150 ℃时摩擦系数均值高达0.117，标准差高达0.024 5，磨损率也急剧升高. 这一现象说明高温持续作用，会引起树脂黏附剂氧化分解，导致复合材料的承载能力和耐磨性能下降[26-27].

图4所示为不同温度和频率下的摩擦系数和磨损率. 25 ℃时，随着频率的增加，复合材料摩擦系数和磨损率逐渐降低. 频率对纤维性能的影响导致材料的摩擦学行为较为复杂[28]，并且频率的改变对于复合材

料的影响可以定义为滑动界面处温度对材料的影响，而材料本身为热的不良导体[2]. 当频率增大至10 Hz时，材料摩擦表面温度急剧攀升，相应地，材料摩擦系数和磨损率呈现减小趋势，如图4所示. 当温度开始升高时，摩擦系数和磨损率先降低后升高并在75 ℃时达到最小值. 综上所述，温度对于材料摩擦磨损性能的影响更为直接. 50~75 ℃时，温度的作用使得树脂黏附剂软化，在摩擦过程被对偶抛光，造成材料的摩擦系数降低[29]. 但温度升高至100 ℃以上，会导致材料承载能力下降，耐磨性能降低.

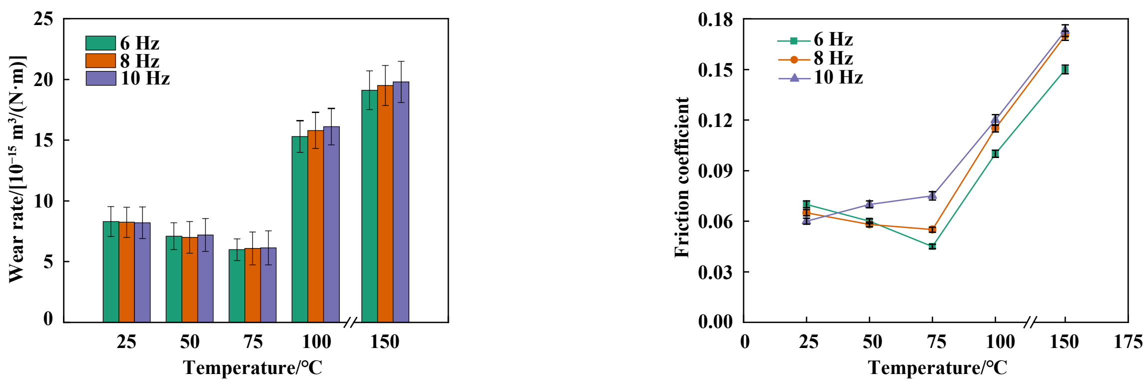
图5所示为不同温度和载荷下的摩擦系数和磨损率，随着温度的增加，材料摩擦系数和磨损率均保持



(a) Wear rate　　(b) Friction coefficient

Fig. 3　Wear rate and friction coefficient at different temperatures (30 MPa, 6 Hz)

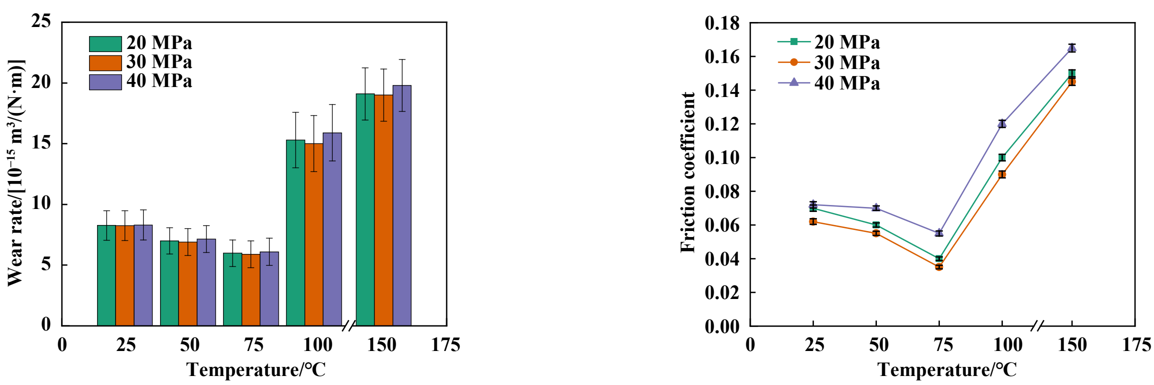
图 3　不同温度下磨损率和摩擦系数(30 MPa, 6 Hz)



(a) Wear rate　　(b) Friction coefficient

Fig. 4　Wear rate and friction coefficient at different temperatures and frequencies (30 MPa)

图 4　不同温度和频率下磨损率和摩擦系数(30 MPa)



(a) Wear rate　　(b) Friction coefficient

Fig. 5　Wear rate and friction coefficient at different temperatures and loads (6 Hz)

图 5　不同温度和载荷下磨损率和摩擦系数(6 Hz)

先减小后增大的规律. 但相同温度下，载荷为30 MPa时，材料摩擦系数和磨损率最小. 载荷的增大使得少量PTFE脱粘[30]，在往复运动时，均匀铺展到摩擦表面，起到减摩的效果. 当载荷增至40 MPa，酚醛树脂因其较弱的热传导能力，加之高温环境中的材料受到严重的压缩和剪切作用，诱导更多摩擦热的产生[31]，使得树脂基体的承载能力大幅下降，失去保护的纤维被金属切断，产生严重的磨损. 所以，在温度与载荷的协同作用下，温度对材料力学性能产生影响，载荷可以影响纤维的挤出形式. 载荷为30 MPa时，在磨损过程中可以起到适当的减摩作用.

2.2 磨损机制

利用扫描电镜(SEM)对材料磨损面、磨屑和转移膜进行观察. 图6所示为不同温度下的磨损形貌的SEM照片和EDS结果. 25 ℃时[图6(a)]，编织结点处出现局部应力集中现象，磨损表面出现明显裂纹，材料表面F元素质量分数约为26.5%，摩擦表面的PTFE纤维被滑动挤出. 随着温度升高至75 ℃[图6(b)]，材料摩擦磨损性能最好(图3)，磨损表面F元素质量分数达到最大值34.2%. 相较于图6(a)，磨损表面的裂纹明显减少，PTFE纤维在热应力的作用下被挤压并且捻碎，形成磨屑，沿着滑动的方向产生塑性流动，从而抑制了裂纹的产生，使得复合材料能够保持良好的力学稳定性和耐磨性能.

当温度升高至150 ℃ 时[图6(c)]，材料表面极为平整，无明显的纤维束. 过高的温度导致材料的结构稳

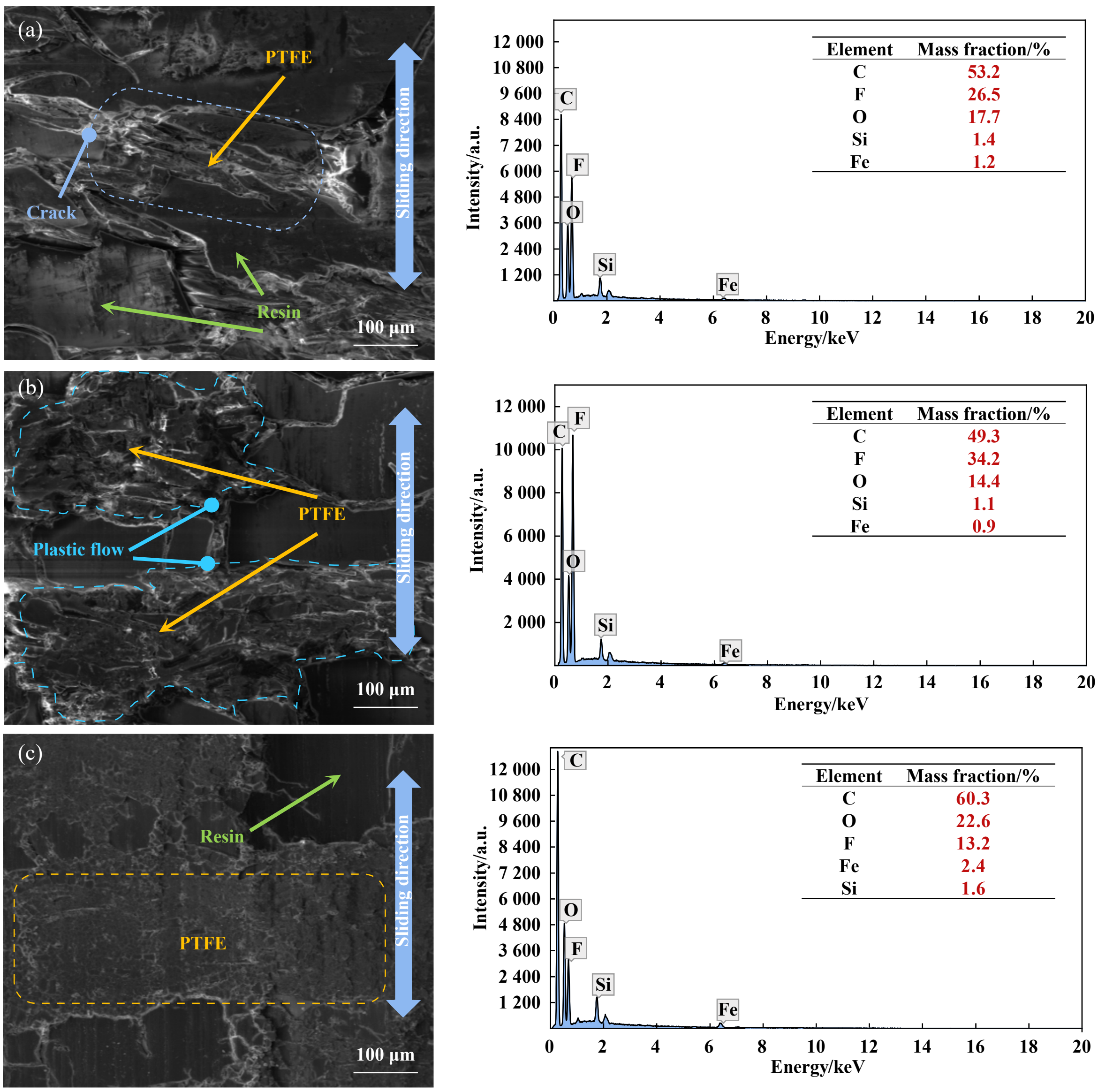


Fig. 6 SEM micrograph and EDS results of worn surfaces at different temperatures: (a) 25 ℃; (b) 75 ℃; (c) 150 ℃ (30 MPa, 6 Hz)

图 6 不同温度下磨损表面的SEM照片和EDS结果：(a) 25 ℃; (b) 75 ℃; (c) 150 ℃ (30 MPa, 6 Hz)

定性急剧降低，PTFE纤维被切断和拔出，形成大片的剥落坑. 磨损表面F元素质量分数减少至13.2%，O元素与Fe元素含量明显增大. 综上所述，复合材料在摩擦过程中摩擦学性能主要与PTFE的磨损行为有关，随着温度的改变，PTFE纤维的挤出方式由滑动挤出转变为切断和拔出.

图7所示为未磨损表面和不同温度下磨损表面的F元素分布. 分析表明，PTFE纤维在初始状态主要分布在编织结点处. 在不同温度下进行摩擦磨损试验后，25 ℃时[图7(b)]，F元素主要处于分散团聚的状态. 由于树脂韧性较差，在编织结点处被冲击，发生断裂，PTFE纤维被附带着剪切挤出. 75 ℃时[图7(c)]，温度的作用使得PTFE纤维表面的树脂软化，黏附到对偶表面，PTFE逐渐向四周流动，使得编织结点处F元素均匀分布，更多的PTFE纤维被挤出，参与到摩擦过程中. 当温度升高至150 ℃时[图7(d)]，F元素分布明显减少，大多直接分布在编织结点处. PTFE被直接挤压切断，这也导致转移膜的生成率降低.

图8所示为不同温度下磨屑表面微观形貌的SEM照片. 温度在25~75 ℃时[图8(a~b)]，磨屑呈现出块状，对比发现，在75 ℃时磨屑的形状尺寸更为细小. 高温作用使得树脂黏附剂软化，粘连在对偶销表面，减少了PTFE纤维直接被金属表面的凸峰刮擦的情况，使得在高温中软化的PTFE纤维在外力作用下被均匀碾碎，形成较小的颗粒状磨屑. 温度升高至150 ℃时[图8(c)]，磨屑有明显被扯断的痕迹，过高的温度导致纤维发生剥落，最终形成磨屑挤出到磨损表面.

图9所示为不同温度下转移膜微观形貌的SEM照片. 25 ℃时[图9(a)]，对偶销表面转移膜与金属结合能力及热稳定性较差，摩擦过程中，局部高温会造成转移膜剥落，造成转移膜的均匀性较差. 随着温度升高至75 ℃ [图9(b)]，转移膜均匀性和稳定性较好，表面出现少量剥落坑，但剥落坑底部并无明显的机械加工痕迹. 这是因为温度升高，PTFE的黏弹性明显增大[32]，磨损初期，由于温度作用，软化的树脂和PTFE被挤压，转移到对偶销表面，形成1层较薄的基层转移膜，填充到金属销表面的沟槽，避免了之后PTFE在挤出时被刮擦. 随着试验的进行，更多的PTFE粘连在基层转移膜表面，形成了质地均匀且较为稳定的双层转移膜. 当温度升高至150 ℃[图9(c)]，对偶销表面的转移膜呈

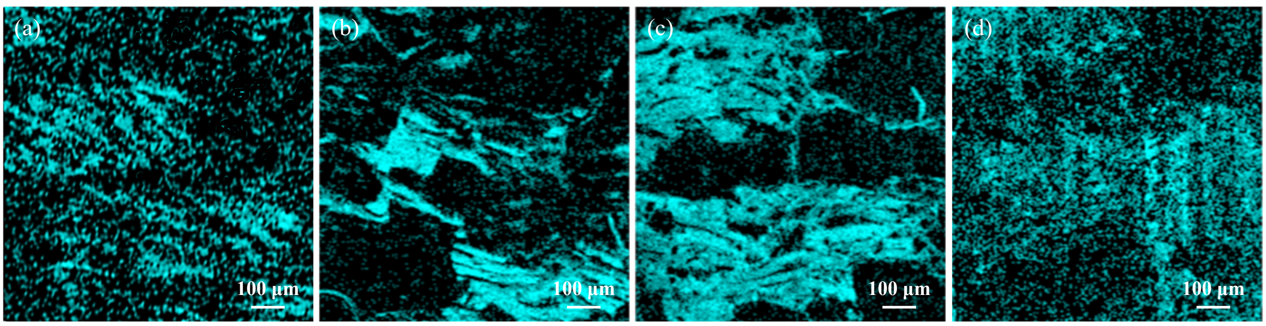


Fig. 7　F element distribution on unworn surfaces and worn surfaces at different temperatures: (a) unworn surfaces; (b) 25 ℃ ; (c) 75 ℃; (d) 150 ℃

图 7　未磨损表面和不同温度下磨损表面F元素分布：(a)未磨损表面；(b) 25 ℃；(c) 75 ℃；(d) 150 ℃

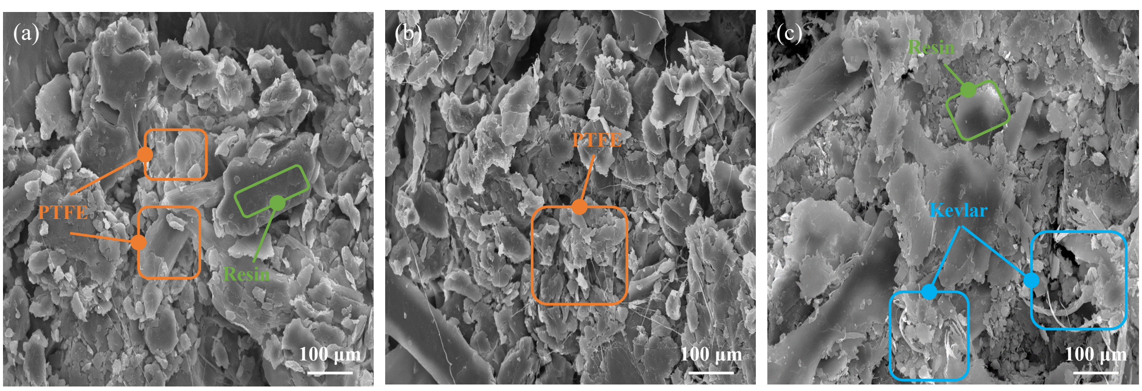


Fig. 8　SEM micrographs of composite material debris at different temperatures: (a) 25 ℃; (b) 75 ℃ ; (c) 150 ℃

图 8　不同温度下复合材料磨屑的SEM照片：(a) 25 ℃；(b) 75 ℃；(c) 150 ℃

现堆积状. 过高的温度对材料的稳定性造成了破坏，树脂无法对PTFE纤维起到保护的功能，多数的PTFE纤维被直接滑动拔出，堆叠形成非均匀的局部层片状转移膜，从而造成在此条件下的非正常磨损.

图10所示为不同温度下的磨损机制示意图，如图10(a)所示，复合材料接触界面处的金属销表面存在着粗糙的凹坑[33]，在室温时，材料表面编织结点处的PTFE纤维由于其剪切强度较低[34]，会发生断裂，从而被碾碎形成磨粒. 由于PTFE的不粘性，金属销表面难以形成均匀且稳定的转移膜. 此时材料的磨损机制以磨粒磨损为主.

当温度升高至75 ℃[图10(b)]，金属销表面温度较高，在摩擦过程中，树脂受热发生软化，黏附在金属销表面，使其表面凹坑得到填充. PTFE纤维因其优良的化学稳定性和性质较软这一特性，促使PTFE纤维充分被捻碎，形成润滑层，起到减摩作用，防止Kevlar纤维断裂. 此外，外部高温作用下PTFE纤维软化，粘连到对偶销表面，与黏附在表面的树脂结合，形成均匀且稳定的转移膜，此时磨损机制主要为轻微黏着磨损. 当温度达到150 ℃[图10(c)]，由于PTFE纤维的机械性能随着温度的升高而降低[35]，材料整体热量快速积累，结构稳定性遭到破坏，树脂受热发生氧化分解，PTFE纤维被大量拔出和切断，挤出到磨损面，无法在材料表面发生塑性流动. Kevlar纤维直接与金属销接触，Kevlar纤维的力学性能随温度的升高而降低[36]，在高温作用下发生断裂，材料强度遭到破坏，产生剧烈磨损，对偶销表面生成的转移膜由于温度较高，产生热疲劳剥落. 此时的磨损机制主要为严重的黏着磨损.

综上所述，随着环境温度从25 ℃升高至150 ℃，复合材料与对偶销之间的磨损机制从磨粒磨损转变为轻度黏着磨损，再转变为严重黏着磨损并伴随着热复合性疲劳剥落. 相应地，PTFE的损伤行为由滑动剪切挤出到粘连，再到纤维的拔出切断与转移膜的消耗以及Kevlar的断裂.

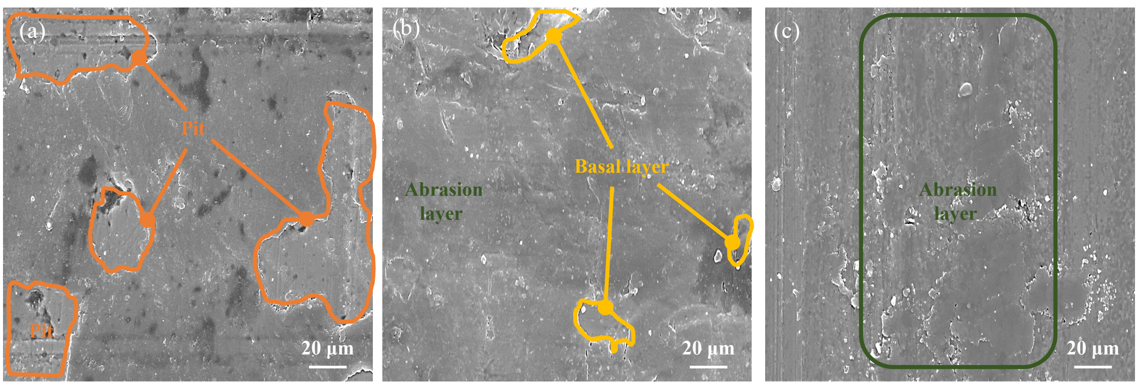


Fig. 9 SEM micrographs of transfer films at different temperatures: (a) 25 ℃; (b) 75 ℃ ; (c) 150 ℃

图 9 不同温度下转移膜的SEM照片：(a) 25 ℃；(b) 75 ℃；(c) 150 ℃

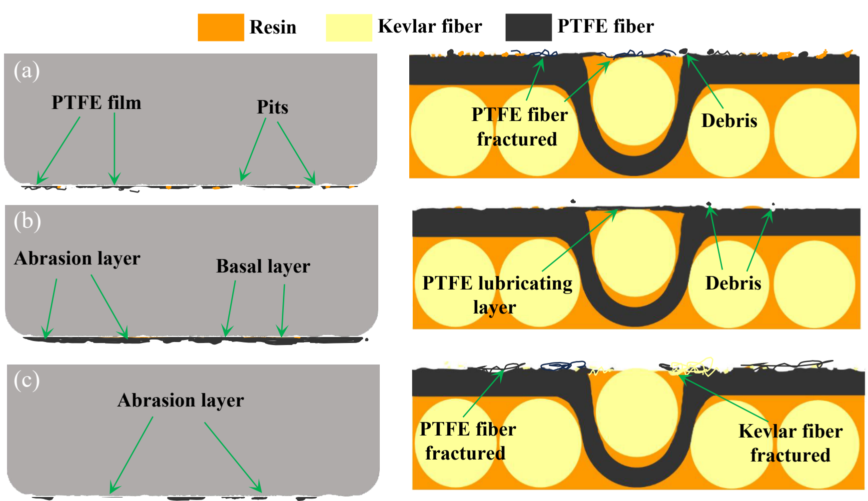


Fig. 10 Illustration of wear mechanism at different temperatures: (a) 25 ℃; (b) 75 ℃; (c) 150 ℃

图 10 不同温度下磨损机制示意图：(a) 25 ℃；(b) 75 ℃；(c) 150 ℃

3 结论

a. 载荷与频率一定时，当温度从25 ℃增加到150 ℃，PTFE/Kevlar织物复合材料摩擦系数和磨损率先减小后增大. 该材料在摩擦温度为75 ℃时，表现出极佳的摩擦磨损性能，摩擦系数约为0.039，超过100 ℃时，摩擦系数波动较大，材料发生剧烈磨损.

b. 温度对材料摩擦学特性的影响远大于频率和载荷. 在载荷与频率的共同作用下，当温度为75 ℃时，PTFE纤维塑性流动现象极其明显，磨损表面F元素质量分数占比高达34.2%，此时摩擦系数波动较为稳定，标准差低至0.005 3. 受温度的影响，PTFE纤维断裂行为由滑动剪切挤出逐渐转变为纤维拔出和切断.

c. 随着温度的升高，复合材料的磨损机制由磨粒磨损转变为轻微黏着磨损，再转变为严重的黏着磨损. 为保证自润滑材料的抗磨损性能，摩擦温度在50~75 ℃时，可以使复合材料长期维持在轻微黏着磨损阶段，提高了材料的自润滑性能和抗磨性能. 当摩擦温度超过100 ℃时，材料黏着磨损和疲劳磨损加剧，极易产生非正常磨损.

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