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摘要集

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目　录

树脂性能及制备工艺对超高分子量聚乙烯纤维/水性聚氨酯复合材料抗弹性能影响

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摘要：选用水性聚氨酯为基体，超高分子量聚乙烯（UHMWPE）纤维为增强体，制备了单向正交结构的复合材料软质防弹层。基于弹道侵彻试验和无损检测表征研究了树脂模量、树脂含量和纤维展开程度对先进复合材料软质防弹层抗弹能力的影响。研究结果显示：采用低树脂含量、低模量树脂以及适当排布速率制备的UHMWPE复合材料展现出更为优异的弹道侵彻性能。低树脂含量提高了纤维占比，使得单位面密度内更多纤维承力；低模量树脂可以降低复合材料的刚度，允许更多次影响区域的纤维拔出和断裂；较快排布速率虽然可以提高生产效率，但是会产生更大的张力，在生产过程中对纤维产生损伤。通过分析各因素对复合材料弹道性能的影响，可以更好地设计弹道复合材料工艺参数，制备出先进复合材料软质防弹层。

关键词：工艺参数；超高分子量聚乙烯纤维；水性聚氨酯；弹道性能

中图分类号：TB332　　**文献标识码：**A

Effect of resin properties and preparation processes on the anti-elastic properties of UHMWPE fiber/waterborne polyurethane composites

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Abstract: Using waterborne polyurethane as matrix and ultra-high molecular weight polyethylene (UHMWPE) fiber as reinforcement, unidirectional and orthogonal composite soft bulletproof layer was prepared. Based on ballistic penetration test and nondestructive testing, the effects of resin modulus, resin content, fiber development degree and other technological parameters on the elastic resistance of the soft bulletproof layer of advanced composites were studied. The results showed that the UHMWPE composites prepared with low resin content, low modulus resin and proper placement rate showed better ballistic penetration performance. The low resin content increases the fiber proportion, resulting in more fiber bearing capacity per unit surface density. The low modulus resin can reduce the stiffness of the composite, allowing more fibers to pull out and break in the affected area. Although the faster arrangement rate can improve the production efficiency, it will generate more tension and damage the fiber during the production process. By analyzing the influence of various factors on the ballistic properties of composites, the technological parameters of ballistic composites can be better designed and the soft bulletproof layer of advanced composites can be prepared.

Key words: Process parameters; Ultra high molecular weight polyethylene fiber; Waterborne polyurethane; Ballistic performance

二维和三维织物结构靶板的防弹性能有限元分析

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摘　要：与传统的二维织物复合靶板相比，三维角联锁织物层间有接结纱线连接，可以有效改善复合靶板的层间开裂损伤；且曲面成型性好，用于制作防弹头盔可以一次成型，不需剪裁。然而不同的纤维集合体结构对复合靶板弹道吸能的影响机制尚不明确。本研究设计织制了相同面积克重、相同纱线排列密度、不同组织结构的三维和二维织物，并加工成预浸料。通过弹道测试和有限元模拟对比分析织物内纱线集合体结构对防弹性能的影响。弹道测试结果表明：具有相同材料重量、相同纱线排列密度的四层接结三维角联锁织物与四层斜纹织物靶板的弹道吸能接近，均低于同纱线细度的四层平纹织物。四种织物制备的预浸料靶板也存在同样的规律。有限元分析结果表明：与二维织物相比，三维角联锁织物内平直纱线上应力传递速度更快，应力分布面积更大。在三维角联锁织物内接结纱屈曲率高，易提前断裂，因此的耗能较少。

关键词：三维角联锁织物；二维平纹织物；弹道吸能；有限元分析；防弹性能

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Finite element analysis of 2D/3D fabric architecture on ballistic performance of armor-grade panel

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Abstract: In comparison with the common two-dimensional（2D）fabric reinforced composite panel, the three-dimensional（3D）angle-interlock fabric possesses the binding warp yarns through the thickness direction, which not only exhibits obvious better interlayer delamination resistance, but also displayed excellent mouldability for the curved surface, which can be applied for complex doubly-curved shapes without cutting. However, it is still not fully understood that the mechanisms of different fibers assembly structures of fabrics on ballistic energy absorption of composite target plates. In this study, several 3D and 2D fabrics with the same areal weight and weave density, but with different weaves were manufactured and processed into the laminated panels. Ballistic tests and Finite Element (FE) simulation are used for investigation. Experimental results show that for a given areal weight of fabric and weave density of yarns, the angle-interlock fabric（TW_4）displayed similar energy absorption as the four-layer twill fabric (TW_4), but lower than that of the four-layer plain fabric（PW_4）with the same yarn count. Fabric laminated panel exhibited the same trend. FE results show that in the 3D angle-interlock fabric, the stress wave velocity is faster in the straight warp and weft yarns in comparison with the 2D fabric. The binding warp yarns in the 3D angle-interlock fabric are prone to failure earlier due to even higher crimp ratio, which result in less energy dissipation.

Keywords: Three-dimensional（3D）angle-interlock fabric; Two-dimensional（2D）plain fabric; Ballistic energy absorption; Finite element analysis; Ballistic performance

碳纤维蜂窝复合材料成型结构对压缩性能的影响

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摘要：为了明确碳纤维蜂窝复合材料的成型结构对其抗压缩性能的影响，本研究采用一维单向铺层、二维织物铺层和三维机织一体成型结构制备了相同规格的碳纤维蜂窝复合材料，通过压缩性能实验，对比了三种碳纤维蜂窝复合材料的抗压缩性能及其损伤失效模式。实验结果表明：三种碳纤维蜂窝复合材料的面外压缩强度差别不大，远高于面内压缩强度（约十倍以上）。但是这三种结构的面内压缩强度差异较大，一维单向铺层蜂窝复合材料的面内 X 方向压缩强度明显高于二维铺层和三维机织蜂窝复合材料，分别高出 41%和 36%。而在面内 Y 方向，三维机织蜂窝复合材料呈现出明显的优势，其压缩强度比一维单向和二维织物蜂窝复合材料分别提高了 20%和 39%，且在压缩过程中没有出现层间开裂，说明蜂窝壁的连接方式能够在一定程度上改善面内抗压缩性能。

关键词：碳纤维蜂窝复合材料；单向铺层结构；平纹铺层结构；三维机织蜂窝预制件；压缩性能

中图分类号：TB332 **文献标识码：**A

The influence of carbon fiber honeycomb composite forming structures on compression performance

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Abstract： To investigate the influence of the forming structure of carbon fiber honeycomb composites on their compressive performance, this study fabricated carbon fiber honeycomb composites with identical specifications using three different forming structures: unidirectional one-dimensional layup, two-dimensional fabric layup, and three-dimensional woven integral forming. Compression tests were conducted to compare the compressive resistance and damage failure modes of the three types of composites. The results revealed that the out-of-plane compressive strengths of all three composites were comparable and substantially higher than their in-plane compressive strengths (by approximately tenfold). However, significant variations were observed in their in-plane compressive performance. The unidirectional one-dimensional honeycomb composite exhibited 41% and 36% higher compressive strength in the in-plane X-direction compared to the two-dimensional and three-dimensional composites, respectively. In the in-plane Y-direction, the three-dimensional woven composite demonstrated superior performance, with compressive strengths 20% and 39% greater than those of the unidirectional and two-dimensional composites. Moreover, no interlayer delamination occurred during compression, indicating that the honeycomb wall connection method can effectively enhance in-plane compressive resistance.

Key words： Carbon fiber honeycomb composite; Unidirectional laminate structure; Plain-woven laminate structure;3D woven honeycomb preform; Compressive performance.

柱形破片侵彻 UHMWPE 层合板多尺度仿真模型

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摘要：为分析 UHMWPE 层合板抗侵彻变形失效机制，建立了硬质合金破片侵彻 UHMWPE 层合板多尺度数值仿真模型，模型中层合板与破片直接作用区及鼓包变形区采用纤维束的中尺度模型，层合板边界采用基于宏观力学响应的复合材料层合结构等效模型。仿真获得不同下层合板鼓包变形规律，鼓包运动速度与破片速度呈正相关，拟合系数φ值为 0.335–0.395。层合板中由于奇数层和偶数层 UD 布呈正交关系，由此引起了奇数层与偶数层中的应力波传播的正交各向异性，无纬布结构 UHMWPE 层合板鼓包形态由侵彻过程中“正方形”演变为最终的拟圆形。侵彻过程中纤维层合板中分层破坏范围在沿弹道方向的剖面上呈现先增大后减小的规律，随着入射速度的提高，当破片的入射速度小于弹道极限时，分层破坏范围增长较快，当破片入射速度大于弹道极限时，靶板分层范围增长速度放缓。结果表明，层合板中心作用区域采用中尺度模型可以实现对材料鼓包过程的准确描述，层合板鼓包形态与试验结果基本一致。

关键词：冲击动力学；侵彻；超高分子量聚乙烯，层合板；多尺度模型

中图分类号：O346.5　　**文献标识码：**A

Study on penetration mechanism of rigid fragments to UHMWPE laminates

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Abstract： In order to reveal the interaction mechanism between the killing element and UHMWPE laminates, the ballistic test of cemented carbide spherical fragments penetrating UHMWPE laminates was carried out. The residual velocity of the fragments penetrating the laminates at different incident velocities and the fracture failure morphology of the laminates at different velocities were obtained. On this basis, based on the wave theory and energy conservation, the energy dissipation model of spherical penetrating into laminated plates was established, and the energy transfer laws of different forms in the process of fragment penetration are analyzed. It is found that the energy transfer caused by shear failure of the middle-layer composite plate in the penetration process is dominant in various forms of dissipated energy, followed by tensile failure. The comparison with the experimental results shows that the model established in this paper can effectively describe the penetration process of the fragment into the laminated plate, which can provide certain reference for the killing mechanism and trajectory design of the protective target.

Key words： impact dynamics, penetration, UHMWPE, laminates, multi-scale model

防弹复合材料与金属高速冲击快速等效分析方法研究

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摘要：随着复合材料在冲击防护、防弹防爆等领域的广泛应用，其冲击防护性能等效评估方法成为结构设计的关键问题。本研究提出了一种基于弹道极限和吸能特性的芳纶复合材料与金属冲击等效分析方法和抗冲击性能评估体系。首先通过高速冲击打靶试验验证高保真芳纶复合材料数值模型；基于建立的冲击模型对比分析金属与芳纶复合材料平板在不同冲击速度下的吸能演化机制，量化其能量耗散差异。之后基于 L-J 弹道极限理论，建立合理化的复材-金属吸能等效模型，揭示不同厚度下金属和复合材料的冲击等效关联性，提出的等弹道极限等效模型弥补了等能量模型的缺陷。结果表明，所提出的等效方法能较好地预测不同厚度的金属板与复合材料在较高冲击速度下的能量吸收等效关系。本研究建立的等效评估体系为复合材料防弹防爆结构设计提供了理论参考。

关键词：芳纶复合材料；高速冲击；防弹金属；冲击等效方法；吸能

中图分类号：V231.9 **文献标识码：**A

Equivalency methods for high-velocity impact bullet-proof composites and metal

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Abstract： The equivalence method of the impact performance of composite materials has become an important issue in structural design with the wide application of composite materials in impact and ballistic protection. This study proposes an impact equivalency analysis method between aramid fiber-reinforced composite material(AFRP) and metal based on ballistic limit and energy absorption characteristics, and evaluation system. First, a high-fidelity numerical model of AFRP is verified by high-speed impact target test. Based on the established impact model, the energy absorption evolution mechanism of metal and aramid composite flat plate at different impact velocities is comparatively analyzed to quantify the difference in energy dissipation. Then, based on the L-J formula, a reasonable equivalent model for the energy absorption of composites and metals is established. The impact equivalent correlation between metals and composites with different thicknesses is revealed, and the proposed iso-ballistic limit equivalent model compensates for the defects of the iso-energy model. The results show that the proposed equivalence method can better predict the energy absorption equivalence correlation between metal plates of different thicknesses and composite materials at high-velocity impact. A theoretical reference for the design of ballistic and blast resistant composite structures is provided by the equivalency evaluation system established in this study.

Key words： Aramid composites, high-velocity impact, bullet-resistant metal, impact equivalence method, energy absorption

石墨烯对超高分子量聚乙烯纤维蠕变行为的影响规律研究

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摘要：通过双螺杆挤出机制备了石墨烯含量为 0%~15%的超高分子量聚乙烯（UHMWPE）纤维，采用恒定载荷蠕变实验测定了纤维的蠕变伸长率与蠕变速率，利用 Burgers 模型对蠕变行为进行了预测。结果表明，当石墨烯含量从 0%增加到 8%时，纤维抗蠕变性能不断提高：在载荷加载的初始阶段（7.5 s 内），蠕变伸长率ε7.5 从 2.23%降至 1.41%，蠕变速率 dε7.5 从 0.28 s-1 下降到了 0.19 s-1；在载荷稳定阶段，蠕变伸长率ε12000 从 7.95%降至 3.86%，蠕变速率 dε12000 从 3.67×10-4 s-1 下降到了 1.83×10-4 s-1。石墨烯含量超过 8%后，因团聚导致分散不均，纤维抗蠕变性能降低，团聚还抑制了聚乙烯大分子伸直链晶的生成，纤维第一和第二吸热峰峰值温度下降。Burgers 模型可以很好预测不同石墨烯含量下纤维的蠕变行为，预测结果与实验结果的均方误差低于 0.06。随着石墨烯含量的增加，模型弹性模量 EM、EK 以及粘度ηM、ηK 参数明显增加，验证了石墨烯对分子链滑移的抑制作用。随着石墨烯含量的增加，纤维弹性模量从纯纤维的 130.3 GPa 增加到了 15%石墨烯含量下的 210.3 GPa，当石墨烯含量超过 8%时，纤维弹性模量实验值低于 Mori-Tanaka 理论预测结果。

关键词：超高分子量聚乙烯纤维；石墨烯；Burgers 模型；蠕变；Mori-Tanaka 理论；预测

中图分类号：TQ342　　**文献标识码：** A

Study on the influence of graphene on the creep behavior of ultra-high molecular weight polyethylene fibers

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Abstract: UHMWPE fibers with graphene content ranging from 0% to 15% were prepared via a twin-screw extruder. The creep strain and creep rate of the fibers were measured using constant - load creep tests, and the creep behavior was predicted using the Burgers model. The results showed that as the graphene content increased from 0% to 8%, the fiber's creep resistance improved. Within the initial 7.5 s of loading, the creep strain ε7.5 decreased from 2.23% to 1.41%, and the creep rate dε7.5 dropped from 0.28 s-1 to 0.19 s-1. During the stable loading stage, the creep strain ε12000 fell from 7.95% to 3.86%, and the creep rate dε12000 decreased from 3.67×10-4 s-1 to 1.83×10-4 s-1. However, when the graphene content exceeded 8%, fiber agglomeration reduced the creep resistance. Agglomeration also inhibited the formation of extended-chain crystals of polyethylene macromolecules, causing the peak temperatures of the fiber's first and second endothermic peaks to decline. The Burgers model could predict the creep behavior of fibers with different graphene contents well, with a mean square error between the predicted and experimental results below 0.06. As the graphene content increased, the model's elastic modulus (EM, EK) and viscosity (ηM, ηK) parameters rose significantly, confirming graphene's inhibition on polymer chain slippage. As the graphene content increased, the fiber's elastic modulus rose from 130.3 GPa for pure fibers to 210.3 GPa for fibers with 15% graphene content. When the graphene content exceeded 8%, the experimental values of fiber elastic modulus were lower than the theoretical predictions of the Mori-Tanaka model.

Keywords: ultra high molecular weight polyethylene fiber; graphene; Burgers model; creep; Mori-Tanaka theory; prediction

单组分水性环氧树脂基超高分子量聚乙烯纤维复合材料的性能研究

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摘要：合成了一种适用于超高分子量聚乙烯纤维（UHMWPE）无纬布的单组分水性环氧树脂（WER），采用缠绕-复合-热压工艺制备单向UD正交结构的无纬布及复合板材。研究了环氧树脂的耐高低温及老化性能、WER基UHMWPE无纬布在加速老化试验下的储存稳定性、复合材料板材在不同温度下的力学性能及弹道极限V50值。结果表明，环氧树脂具有较好的耐高低温性能，其拉伸剪切强度在80℃下还能维持在一个较高的水平，且在低温-40℃下，性能与常温状态相比并无下降；通过加速老化实验模拟和阿伦尼乌斯公式计算，环氧树脂在23℃环境中约279天才会出现性能衰减；WER基无纬布具有较好的储存稳定性，能在23℃环境中约117天保证性能不衰减；通过V50来评价材料在高低温环境中的防弹性能，WER基复合材料经过400h的双85老化后防弹性能几乎没有变化。

关键词：超高分子量聚乙烯（UHMWPE）纤维；单组分水性环氧树脂；耐高低温；储存稳定性

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Performance study of single-component waterborne epoxy resin-based ultra-high molecular weight polyethylene fiber composites

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Abstract： A one-component waterborne epoxy resin (WER) suitable for ultra-high molecular weight polyethylene (UHMWPE) fiber non-woven fabric was synthesized. Unidirectional (UD) orthogonal non-woven fabric and composite panels were prepared using a winding-composite-hot pressing process. The resin's resistance to high/low temperatures and aging properties were investigated, along with the storage stability of WER-based UHMWPE non-woven fabrics under accelerated aging tests. The mechanical performance of composite panels at different temperatures and the ballistic limit V50 value were also studied. The results indicate that the epoxy resin exhibits favorable high temperature resistance, the tensile shear strength of WRE resin is maintained at a high level at 80°C， And at a low temperature of -40°C, the performance does not decrease compared with the normal temperature state. Through accelerated aging simulations and calculations using the Arrhenius equation, the epoxy adhesive demonstrates performance attenuation after approximately 279 days in a 23°C environment. The WER-based non-woven fabric displays excellent storage stability, maintaining stable performance for about 117 days under 23°C conditions. Evaluated through V50 ballistic testing, the ballistic performance of WER matrix composites was almost unchanged after 400h with testing under Double 85 conditions .

Key words: Ultra-high molecular weight polyethylene (UHMWPE) fiber; single-component waterborne epoxy resin; high/low-temperature resistance; storage stability

超高分子量聚乙烯纤维在防弹防爆复合材料中的应用进展

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摘要：超高分子量聚乙烯纤维凭借其高比强度、轻量化及优异能量吸收能力，已成为防弹防爆复合材料的核心组分。深入剖析了超高分子量聚乙烯纤维的特性及其在复合材料防护机制中的核心作用，系统评述了其在陶瓷复合装甲、金属层合结构及混杂体系等关键应用领域的最新研究进展与性能优化策略。重点探讨了基于先进表面功能化、仿生梯度/多级结构以及多功能集成等创新策略在提升界面强度、能量吸收效率和抗多次冲击能力方面的突破性进展。尽管取得显著进展，其固有的耐热性瓶颈、高端纤维国产化核心制备技术以及跨尺度仿真与标准化评价体系等深层次挑战仍需攻坚克难。未来发展趋势聚焦于智能响应型复合材料、绿色可持续制造、以及多功能一体化等前沿方向。

关键词：UHMWPE 纤维；防弹防爆；仿生结构设计；界面改性；能力吸收机制；多功能一体化

中图分类号：TB332　　**文献标识码：**A

Advances in the Application of Ultra-High Molecular Weight Polyethylene Fibers in Ballistic and Blast-Resistant Composite Materials

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Abstract： Ultra-high molecular weight polyethylene fibers have become a core component in ballistic and blast-resistant composite materials due to their high specific strength, lightweight nature, and excellent energy absorption capabilities. This paper provides an in-depth analysis of the properties of UHMWPE fibers and their critical role in the protective mechanisms of composite materials. It systematically reviews recent advances and performance optimization strategies in key application areas such as ceramic composite armor, metal-based laminated structures, and hybrid systems. Particular emphasis is placed on innovative strategies—such as advanced surface functionalization, biomimetic gradient/multiscale architectures, and multifunctional integration—that have led to breakthroughs in enhancing interfacial strength, energy absorption efficiency, and resistance to multiple impacts. Despite significant progress, intrinsic challenges remain, including the material's limited thermal resistance, the lack of core domestic production technologies for high-end fibers, and the need for cross-scale simulation and standardized evaluation systems. Future development trends are expected to focus on smart responsive composites, green and sustainable manufacturing, and integrated multifunctional materials.

Key words： UHMWPE fiber； bulletproof and blast-resistant； biomimetic structural design； interfacial modification；energy absorption mechanism；multifunctional integration.

聚硼硅氧烷剪切增稠胶在防弹防爆领域的应用

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摘要：聚硼硅氧烷剪切增稠胶（PBS-STG）是一种兼具剪切增稠特性和高稳定性的智能材料，其独特的动态交联网络结构使其在高速冲击下迅速硬化，有效吸收能量并分散冲击力，而在静态条件下保持柔软轻便的特性。本文系统分析了聚硼硅氧烷的分子结构及性能，以及防弹防爆的作用原理，并重点探讨其在防弹衣、防弹装甲、防爆玻璃、防爆服、防爆容器及盾牌等领域的应用现状。结合最新研究成果，本文还总结了当前技术瓶颈及未来发展方向，为高性能防护材料的研发提供参考。

关键词：聚硼硅氧烷；剪切增稠胶；防弹防爆防护；自修复；能量吸收；轻量化

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Application of polyborosiloxane shear-shickening gel in bulletproof and explosion-proof fields

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Abstract： Polyborosiloxane shear-thickening gel (PBS-STG) is an intelligent material that combines shear-thickening properties with high stability. Its unique dynamic cross-linked network structure enables rapid hardening under high-speed impact, effectively absorbing energy and dispersing impact forces, while maintaining softness and lightweight characteristics under static conditions. This article systematically analyzes the molecular structure and properties of polyborosiloxane, as well as the principle of bulletproof and explosion-proof effects, and focuses on exploring its application status in the fields of bulletproof vests, bulletproof armor, explosion-proof glass, explosion-proof clothing, explosion-proof containers, and shields.By integrating the latest research advances, this study also summarizes existing technical bottlenecks and future development directions, providing insights for the design of high-performance protective materials。

Key words： Polyborosiloxane; shear-thickening gel; bulletproof and explosion-proof; self-healing; energy absorption; lightweighting

混杂纤维复合材料梯度设计及防弹性能

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摘要：本研究对芳纶纤维与超高分子量聚乙烯（UHMWPE）纤维混杂复合材料梯度设计的防弹性能影响进行了探究。设计了 5 种 UHMWPE 含量梯度方案（层数：0/10/20/30/40 层，对应含量 0%-100%），总面密度均严格控制在 6±0.05 kg/m²以下。通过弹道测试（分别以芳纶和 UHMWPE 作为弹击面），系统分析了纤维含量及铺层顺序对层合板弹道极限速度（V50）和弹道性能指数（BPI）的影响规律，并基于实验数据建立了纤维含量与防弹性能的三次项非线性回归定量关系模型（R²>99%），为混杂纤维复合材料的梯度设计与防弹装备开发提供了科学依据。

关键词：混杂纤维；复合材料；梯度设计；芳纶；UHMWPE；弹道极限速度；弹道性能指数

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Gradient design and ballistic performance of hybrid fiber composites

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Abstract：This study investigated the influence of gradient design on the ballistic performance of aramid fiber and ultra-high molecular weight polyethylene (UHMWPE) fiber hybrid composites. Five gradient schemes with varying UHMWPE content (corresponding to 0, 10, 20, 30 and 40 layers, representing 0% to 100% UHMWPE content) were designed, with the total areal density strictly controlled below 6±0.05 kg/m² for all configurations. Ballistic tests were conducted, utilizing both aramid and UHMWPE as the impact faces, to systematically analyze the effects of fiber content and stacking sequence on the ballistic limit velocity (V50) and ballistic performance index (BPI) of the laminates. Based on the experimental data, a cubic nonlinear regression quantitative relationship model ($R^2 > 99\%$) between fiber content and ballistic performance is established，which provides a scientific basis for the gradient design of hybrid fiber composites and the development of ballistic protection equipment.

Key words： Hybrid fibers; Composites; Gradient design; Aramid; UHMWPE; Ballistic limit velocity (V50); Ballistic performance index (BPI)

聚氨酯上浆剂处理对芳纶表面及界面性能的影响

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摘要： 采用水性聚氨酯（WPU）上浆剂对芳纶进行改性，提高芳纶与聚氨酯树脂（TPU）界面结合性能和复合材料的力学性能。采用傅里叶红外光谱仪、X 射线光电子能谱和扫描电镜等对芳纶纤维结构、表面元素组成和表面形貌进行表征，结果表明 WPU 上浆剂成功涂覆在芳纶表面。并对不同 WPU 含量的上浆剂对芳纶纤维表面能、单丝拉伸强度、拉伸强度、层间剪切强度等进行研究。发现不同 WPU 含量都可以提高了纤维表面的粗糙度和表面能；在 WPU 上浆剂质量分数为 0.8wt.%时，其性能提高的最明显，经过 WPU-AF 表面能提高了 28.91%，层间剪切强度为 32.7 MPa 提高了 37.9%。

关键词： 聚氨酯；芳纶纤维；界面结合性能

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Effects of the polyurethane sizing agent on surface and its interfacial properties for the aramid fiber

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Abstract: Waterborne polyurethane (WPU) sizing agent was used to modify aramid fiber (AF)and improve the interfacial bonding properties for AF and polyurethane resin (TPU). The structure, surface element composition and morphology of AF were characterized by Fourier transform infrared spectroscopy, X-ray photoelectron spectroscopy and scanning electron microscopy. The results showed that WPU sizing agent was successfully coated on the AF surface. The effects of WPU content on the surface energy, tensile strength of AF single-filament, interlaminar shear strength of aramid fibers and TPU were studied. It is found can improve the surface roughness and surface energy of fiber surface with various WPU content. When the content of WPU sizing agent is 0.8wt.%, the surface energy of WPU-AF is increased by 28.91%. while the interlaminar shear strength is 32.7MPa, increased by 37.9%.

Key words: polyurethane； aramid fiber； interfacial bondin

陶瓷/超高分子量聚乙烯复合材料装甲板抗穿甲弹侵彻的损伤机制

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摘　要：以陶瓷作为面板材料，超高分子量聚乙烯复合材料层压板（UHMWPE）为背板材料，通过真空袋模压工艺制备陶瓷/超高分子量聚乙烯复合材料装甲板，采用穿甲弹侵彻复合装甲板，研究复合装甲板的抗侵彻性能。基于 X 射线计算机断层扫描（X-ray computed tomography, CT）技术和断口形貌观察，分析复合装甲板的陶瓷破碎行为、弹道侵彻下的损伤模式以及弹道侵彻相应机制。研究结果表明：陶瓷的破碎区域呈现双圆台状；陶瓷的响应区域包括陶瓷板背面的超前破碎区、弹道侵彻后剩余的陶瓷板、弹丸正下方的碎片-完全粉化区；陶瓷内的自由面锥角与复合装甲板的抗穿甲弹侵彻性能存在明显正相关性。弹道侵彻后的复合装甲板的损伤模式包括陶瓷碎裂、陶瓷与 UHMWPE 的界面破坏及 UHMWPE 的绝热剪切破坏、拉伸变形和分层破坏。复合装甲板的响应过程包括冲击波传播过程及诱导陶瓷内自由面生成、陶瓷的破碎过程、陶瓷与 UHMWPE 的界面破坏、UHMWPE 层压板的压缩-剪切-拉伸的耦合过程。

关键词：陶瓷；超高分子量聚乙烯层压板；复合装甲板；穿甲弹；陶瓷破碎；损伤模式；损伤机制

Damage mechanism of ceramic/ultra-high molecular weight polyethylene fiber composite armor plate against armor piercing projectile

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Abstract: The ceramic was used as panel material, and UHMWPE laminate was used as back plate material. Ceramic/UHMWPE composite armor plate was prepared by resin film infusion. The composite armor plate was impacted by armor piercing projectile to study the anti-penetration performance. Based on X-ray computed tomography (CT) technology and fracture morphology observation, the ballistic response mechanism of composite armor plate was analyzed.Further, the fragmentation behavior of ceramics and the damage mode of the post-impact ceramic/UHMWPE composite armor plate were explored. The results show that the damage region of ceramics presents a double cone shape. The response region of the ceramic includes the advanced fragmentation zone on the back face of the ceramic plate, the remaining ceramic plate after ballistic penetration, and the fragment-complete pulverization zone directly below the projectile. There is an obvious positive correlation between the free surface cone angle of B4C ceramics and the anti-penetration performance of composite armor plate.The damage modes of post-impact composite armor plate include SiC fragmentation, interface failure between ceramic and UHMWPE, adiabatic shear failure, tensile deformation and delamination failure of UHMWPE. The response process of ceramic/UHMWPE composite armor plate includes shock wave propagation process and the generation of free surface formation in ceramics, ceramic fragmentation process, and the coupling process of compression, shear, and tension of UHMWPE laminate.

Keywords: ceramics; ultra-high molecular weight polyethylene; composite armor plate; armor piercing projectile; ceramic fragmentation; damage modes; damage mechanism

软质防弹材料在个体防护装备中的应用现状及其发展趋势

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摘　要：本研究旨在系统评估软质防弹材料在个体防护装备中的应用现状，并探讨其发展趋势。通过对比分析对位芳纶机织布、杂环芳纶机织布、对位芳纶无纬布和超高分子量聚乙烯（UHMWPE）无纬布的防弹机理及性能参数，结合弹道冲击试验、力学性能测试及实际应用案例，揭示四类材料的核心差异。研究表明：对位芳纶机织布和杂环芳纶机织布凭借经纬交织结构具备优异抗剪切性能，但在 9mm 铅芯弹比吸能上（190-290J/（kg/㎡））上逊于 UHMWPE 无纬布（270-470J/（kg/㎡）；对位芳纶无纬布通过叠层粘合实现多角度能量吸收，其 9mmV50 值较对位芳纶机织布提升 10%-15%；而 UHMWPE 无纬布凭借 45cN/dtex 以上拉伸强度及低密度特性，在轻量化防护领域占据优势，但存在高温蠕变和低抗剪切性能缺陷。当前应用格局呈现：国外软质防弹层采用对位芳纶/杂环芳纶、对位芳纶无纬布和 UHMWPE 混杂的轻薄软(NIJ IIIA，面密度≥3.17kg/㎡，厚度 5mm 左右)结构特征，国内及其不发达地区采用芳纶/UHMWPE 和抗缓冲材料组合的重厚硬(NIJ IIIA，面密度≥4.4kg/㎡，厚度≥10mm)结构特征。结论指出，未来发展趋势将聚焦于超轻超薄超软防弹材料、多功能防弹材料的研发，通过多尺度结构设计与仿生学原理结合，实现防护性能（NIJ IIIA 级标准下减重 15%-20%）与穿戴舒适性的协同突破。

关键词：软质防弹材料；芳纶机织布；芳纶无纬布；超高分子量聚乙烯（UHMWPE）无纬布；个体防护装备

Application Status and Development Trends of Soft Ballistic Materials in Personal Protective Equipment

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Abstract: This study aims to systematically evaluate the current application status of soft ballistic materials in personal protective equipment (PPE) and explore their development trends. By comparatively analyzing the ballistic mechanisms and performance parameters of para-aramid woven fabrics, heterocyclic aramid woven fabrics, para-aramid unidirectional (UD) fabrics, and ultra-high molecular weight polyethylene (UHMWPE) UD fabrics—combined with ballistic impact testing, mechanical property evaluations, and practical application cases—the core differences among these four materials are revealed. The results indicate that para-aramid and heterocyclic aramid woven fabrics exhibit superior shear resistance due to their warp-weft interlaced structures, but their specific energy absorption (190 – 290 J/(kg/m²)) for 9mm lead-core projectiles is lower than that of UHMWPE UD fabrics (270 – 470 J/(kg/m²)). Para-aramid UD fabrics achieve multi-angle energy absorption through laminated bonding, improving their 9mm V50 values by 10% – 15% compared to para-aramid woven fabrics. UHMWPE UD fabrics dominate lightweight protection with tensile strengths exceeding 45 cN/dtex and low density, yet suffer from high-temperature creep and poor shear resistance. Current application patterns show that foreign soft ballistic layers adopt hybrid lightweight-soft structures (NIJ IIIA, areal density ≥3.17 kg/m² , thickness ~5 mm) combining para-/heterocyclic aramids and UHMWPE, while domestic and underdeveloped regions utilize heavy-hard-thick structures (NIJ IIIA, areal density ≥4.4 kg/m² , thickness ≥10 mm) integrating aramid/UHMWPE with impact-buffering materials. Future trends will focus on ultra-lightweight, ultra-thin, and ultra-soft ballistic materials, as well as multifunctional designs, achieving synergistic breakthroughs in protection performance (15% – 20% weight reduction under NIJ IIIA standards) and wear comfort through multiscale structural design and biomimetic principles.

Keywords: Soft ballistic materials; aramid woven fabrics; aramid unidirectional (UD) fabrics; ultra-high molecular weight polyethylene (UHMWPE) UD fabrics; personal protective equipment

抗冲击复合材料中的纺织增强结构设计研究

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摘　要：以高性能纤维材料为基础的柔性织物和复合材料，能够有效依靠其纺织结构设计，实现防弹、防刺等冲击防护功能，从而为单兵防护装备的轻量化提供可能。 报告将从冲击防护纺织结构研究现状、三维机织柔性防弹织物设计，以及抗冲击三维纺织复合材料设计三方面总结近年来课题组在抗冲击复合材料中纺织结构设计方面的研究进展。以女性防弹衣、一体成型防弹头盔盔壳、防弹防刺（双防）复合材料等为例，展示纺织结构设计在抗冲击性能提升方面的贡献。以期纺织增强结构设计未来能够在个体防护、航天复合材料等领域中发挥更大潜力。

关键词：三维机织物，冲击防护，防弹头盔，防弹防刺

Engineering design of textile reinforcing structures for impact resistant composites

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Abstract: Compliant fabrics and textile reinforced composites based on high-performance fibers can be engineering designed into ballistic and stabbing protective materials, thus providing the possibility for the lightweight personal protective equipment design. This report summarizes the research progress in textile structural design for impact resistant composites in recent years from three aspects: the research progress in impact protective woven textile structures, the design of three-dimensional woven fabrics for soft armors and textile composites. Taking the female body armor, one-piece ballistic helmet shell, ballistic & stab-resistant (dual-protection) composite materials as examples, the contribution of textile structure design to the improvement of impact resistance is demonstrated. It is expected that the structural design of textile reinforcements can contribute more to the lightweight applications in personal protection and aerospace composites in the future.

Keywords: 3D woven fabric，Impact protection，Ballistic helmet，Ballistic & Stabbing Resistant

小口径铅芯弹侵彻软防护靶标能量耗散规律研究

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摘　要：为研究铅芯结构步枪弹在低速条件下撞击软防护明胶的能量释放和传递规律，首先对小口径枪弹侵彻软防护的极限穿透速度进行试验研究，得到该弹侵彻软防护的极限穿透速度，进而对低于该速度下的弹头侵彻软防护明胶进行试验和数值仿真工作，对仿真计算结果的弹头变形、穿透软防护层数、明胶鼓包过程与试验结果对比，验证数值仿真的准确性，进而对数值仿真结果进一步分析，对非贯穿下的枪弹侵彻软防护明胶的受力、能量传递和变化进行分析，得到软防护和明胶吸能关系以及该过程中的能量耗散规律，结果表明，弹头破碎是能量耗散的主要原因，正侵彻下，软防护和明胶吸能随速度增加而增加，弹头耗散能量也不断增加，入射角越大，明胶吸能随入射角增大而减小，弹头耗散能量和软防护吸能占比不断增加。研究结果可为枪弹设计和单兵防护设计提供技术指导。

关键词：SC 弹；能量耗散；传递；软防护

Research on the Energy Dissipation Law of Small-caliber Lead-core Bullets Penetrating Soft Protective Targets

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Abstract: In order to study the energy release and transfer law of rifle bullets with lead-core structure when they impact soft protective gelatin at low speeds, first, an experimental study is carried out on the ultimate penetration speed of small-caliber bullets penetrating soft protection. The ultimate penetration speed of the bullet penetrating soft protection is obtained. Then, experiments and numerical simulations are conducted on the bullet head penetrating soft protective gelatin at speeds lower than this speed. The bullet head deformation, the number of layers of soft protection penetrated, and the gelatin bulging process in the simulation calculation results are compared with the experimental results to verify the accuracy of the numerical simulation. Furthermore, the results of the numerical simulation are further analyzed, and the force, energy transfer, and changes when the bullet penetrates the soft protective gelatin without penetration are analyzed. The relationship between the energy absorption of the soft protection and the gelatin and the energy dissipation law in this process are obtained. The results show that the fragmentation of the bullet head is the main reason for energy dissipation. Under normal penetration, the energy absorption of the soft protection and gelatin increases with the increase in speed, and the energy dissipated by the bullet head also continuously increases. The larger the incident angle is, the smaller the energy absorption of the gelatin is as the incident angle increases, and the proportion of the energy dissipated by the bullet head and the energy absorbed by the soft protection continuously increases. The research results can provide technical guidance for the design of bullets and individual protection.

Keywords: SC bullet; Energy dissipation; Transfer; Soft protection