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异质多孔结构材料的设计策略与抗冲击性能研究进展*

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摘　要：多孔结构材料作为一类轻质高强的功能 - 结构一体化材料，在航空航天、汽车制造和生物医疗等领域应用广泛。然而，传统单一构型的多孔结构材料（如蜂窝结构、点阵晶格）在面对爆炸冲击波、多向冲击或非线性变形等复杂工况时，表现出性能局限。在此背景下，异质多孔结构材料（heterogeneous cellular structure material, HCSM）逐渐成为冲击防护领域的研究热点。系统综述了近年来 HCSM 的设计策略及其抗冲击性能。HCSM 主要分为拓扑构型异质（包括互补型和增强型融合）和材料异质（如泡沫材料与剪切增稠材料的填充）两大类型，通过创新性的“功能融合”途径，实现了对单一构型的多孔结构材料性能瓶颈的突破。进一步梳理了 HCSM 在承受冲击载荷时的协同增强效应与变形机理，深入分析了其在能量吸收效率、刚度与稳定性提升方面的内在机制。尽管 HCSM 的研究已取得显著进展，但仍面临连接性优化、增材制造工艺匹配、复杂工况验证以及多功能集成等诸多挑战。展望未来，融合人工智能与机器学习技术，有望实现 HCSM 从设计到制造的全流程一体化优化，从而为开发新一代高性能抗冲击结构材料提供新的方向。

关键词：异质多孔结构材料；抗冲击；设计策略；功能融合；能量吸收

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多孔结构材料作为一种轻质高强的功能材料，具有高刚度、高比强度、高比吸能、噪声抑制和增强传热/隔热等优异性能，在航空航天、汽车和生物医疗等行业具有广泛的应用。多孔结构材料的发展经历了从简单仿生到精密设计的演进过程[1-5]。对于其优异的抗冲击性能，已通过大量实验、理论和数值研究得到了系统验证。

蜂窝结构是典型的二维多孔结构材料，以高度有序的六边形胞孔为特征，在冲击载荷下能通过孔壁的稳定、有序屈曲来吸收能量，具有极高的比强度和优异的抗压性能，常用于航空航天和车辆装甲的夹层板芯层，能有效分散和抵抗爆炸冲击波[6,7]。泡沫材料是典型的三维多孔结构材料，拥有大量随机分布的非均匀闭孔或开孔，其抗冲击特性源于胞元的逐层塌陷和塑性变形，能将冲击能量高效地转化为塑性变形能，显著延长载荷作用时间、降低主结构收到的峰值载荷，同时兼具轻质、高阻尼和吸声等多功能优势，是理想的爆炸冲击隔离层和缓冲包装材料[8,9]。点阵晶格结构材料作为先进的人工设计多孔结构材料，其三维空间规整排列的桁架结构可实现力学性能的精准调控，不仅具备极高的比刚度和比强度，其开放的结构更利于应力波的快速消散，并通过杆件或者板壳的塑性变形和断裂吸收能量，在航空航天超轻质抗冲击结构和人体防护装备等领域具有广阔前景[10,11]。

随着现代工程对防护性能要求的不断提升，单一均质多孔结构材料在应对爆炸冲击波、多向冲击或非线性变形场景时逐渐暴露出局限性。在爆炸载荷及强冲击载荷下，结构需同时承受高强度压缩和剪切力，而单一的构型可能出现局部失效，降低整体能量吸收效率。此外，均质

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多孔结构材料优化空间有限，难以兼顾低密度、高刚度和多功能性需求。为此，学者们开始探索新的结构与设计，通过深入对比研究，发现梯度或层级多孔结构材料相较于均质多孔结构材料展现出显著优势，可以有效提升能量吸收效率及抗冲击性能[12-14]。其中，梯度多孔结构材料[15-19]通过渐变的孔隙率设计，可以实现优异的应力波阻抗匹配，降低初始冲击峰值力；而单元尺寸或拓扑构型在空间上的梯度分布，能避免结构出现应力集中，抑制裂纹扩展、延缓剪切带形成。这也为多孔结构材料的轻量化抗冲击设计提供了更理想的解决方案。层级设计[20-25]通过在不同尺度上引入有序或无序胞元排列，实现了力学性能的显著跃升。其核心思想在于“多尺度协同”：在宏观尺度上，层级构型能更高效地引导和分布载荷，避免应力集中；同时在细观尺度上，子结构的局部设计可有效提升刚度和能量吸收效率。因此，层级设计多孔结构材料在承受冲击载荷时，能够通过子结构的逐级、有序屈曲与坍塌，将剧烈的整体失效转化为平稳、延展的能量耗散过程。相较于均质多孔结构材料，层级多孔结构材料表现出更高的比强度、比刚度和优异的抗冲击韧性，这在极端或复杂工况应用中尤为关键。

目前针对多孔结构材料的梯度或层级设计大多是对单一拓扑构型的优化设计，始终无法突破性能壁垒，满足高端航空航天装备对轻量化、高强度、高能量吸收和多功能一体化的极致需求。在此背景下，HCSM 逐渐成为冲击防护领域的研究热点，通过不同细观构型及基体材料间创新性的“功能融合”与“多机制协同”，打破传统单一均质结构材料在性能上的固有局限，实现材料性能的跨越式提升。如图 1 所示，HCSM 材料在航空航天领域的高性能发动机叶片与复杂结构件、汽车机械工业领域的碰撞安全装置与精密机械部件，以及人体防护及医疗领域的防护装备中均具有重要的应用价值[26-28]。然而，相较于均质多孔结构材料相对完整和成熟的性能评估及应用开发，对 HCSM 的深入探索与分析较少。本文通过系统梳理 HCSM 的细观构型的设计策略和抗冲击性能，剖析了其发展面临的核心挑战并指明了未来发展方向，为高性能轻量化冲击防护材料的研发提供了重要的理论参考与方向性指导。

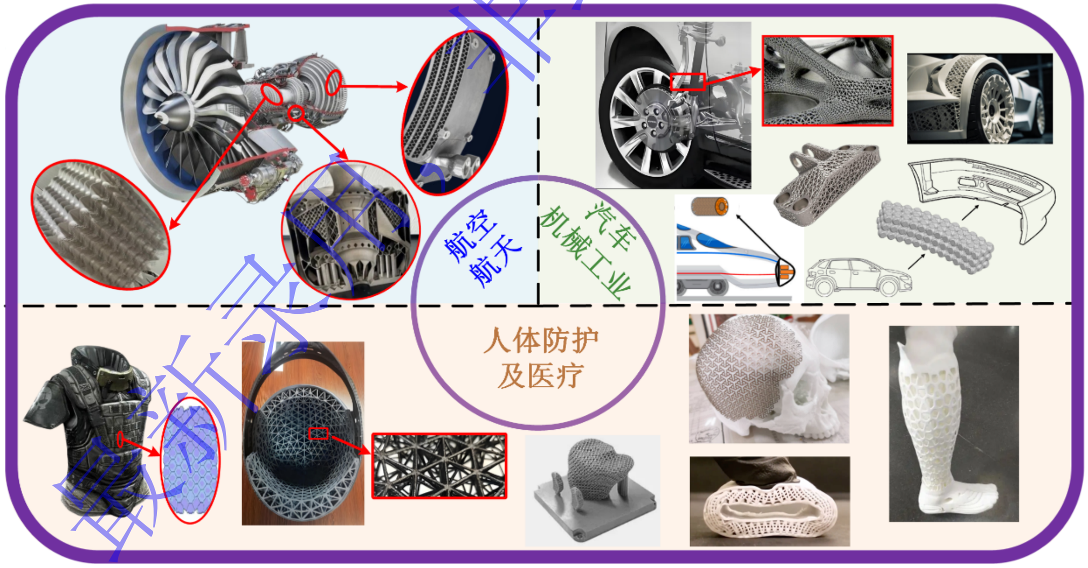

图 1. 异质多孔结构的实际工程应用
Fig.1 Practical engineering applications of HCSM

如图 2 所示，对于 HCSM，将其分为拓扑构型异质与材料异质两大类。在拓扑构型异质中，根据设计策略与功能目标的不同，将其分为互补型异质结构与增强型异质结构两类。在材料异质中，主要分为泡沫填充型和剪切增稠材料填充型两类。

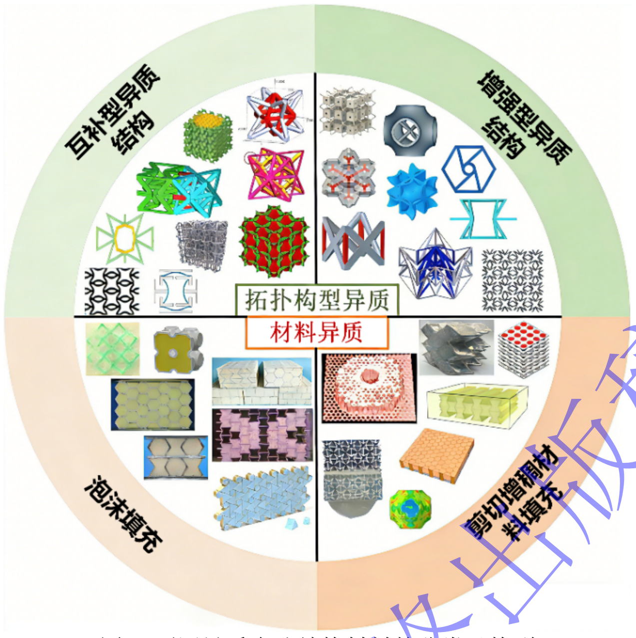

图 2. 不同异质多孔结构材料的分类及构型
Fig.2 Classification and Configuration of Different HCSM

1. 拓扑构型异质多孔结构材料

1. 1 互补型 HCSM

传统单一结构材料受其构型特性限制，高承载能力与高能量吸收之间存在固有矛盾。通过将两种及以上具有互补力学特性的结构进行集成组合，互补型 HCSM 能达到卓越的性能融合与协同增效，突破传统单一结构材料的局限。互补型的设计重在均衡 HCSM 的各项性能指标，实现性能互补，多维度提升多孔结构材料的整体性能。

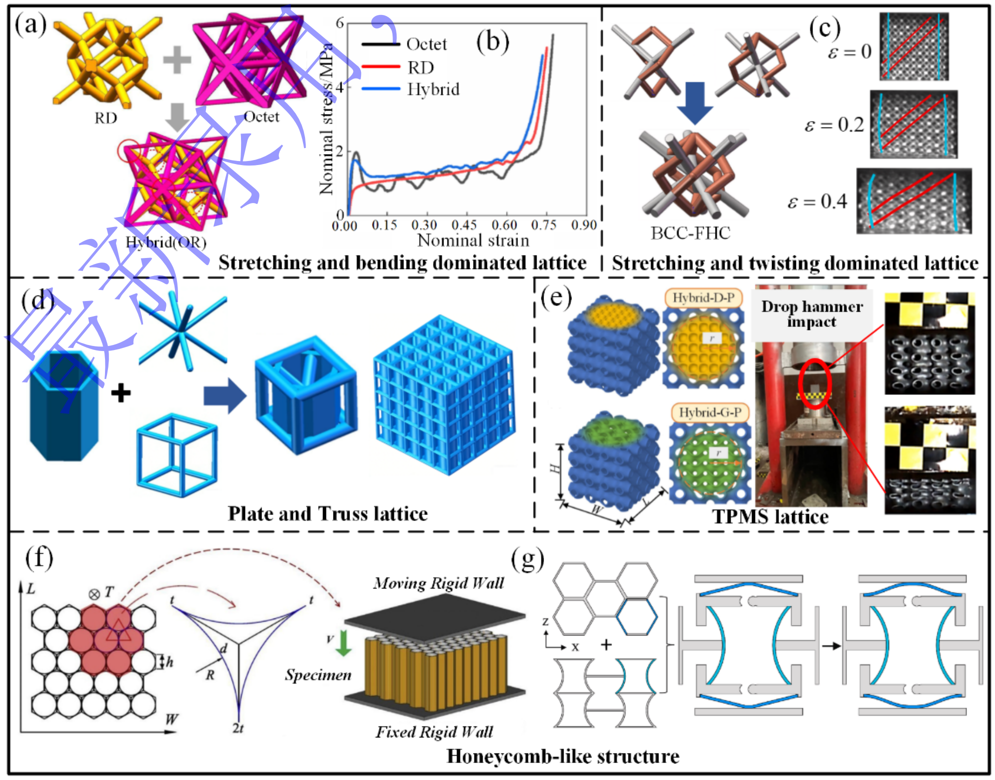

图 3.互补型 HCSMs (a) RD 与 Octet 异质晶格结构融合设计[37] (b) 不同晶格材料的实验应力-应变曲线[37] (c) BCC 胞元与 FHC 胞元异质结构及变形模态[40] (d) 板与桁架晶格融合设计[44] (e) TPMS 晶格径向融合及落锤试验[52] (f) 蜂窝结构内部填充圆管设计[59] (g) 六边形蜂窝与凹圆弧蜂窝结构融合设计[72]

Fig.3 Complementary HCSMs: (a) RD and Octet Hetero-lattice Fusion Design[37] (b) Experimental Stress-Strain Curves of Different Lattice Materials[37] (c) BCC and FHC hybrid structures and deformation modes[40] (d) Plate-Truss Lattice Fusion Design[44] (e) Radial Lattice Fusion of TPMS and Drop hammer impact test[52] (f) Circular Tube Filling Design for Honeycomb Structures[59] (g) Fusion Design of Hexagonal Honeycomb and Concave Circular Arc Honeycomb Structures[72]

1.1.1 晶格类

根据单元支柱变形模式和整体变形机制，以及麦克斯韦准则，晶格结构通常分为拉伸变形主导或弯曲变形主导[29]。传统拉伸主导结构[30-32]，如四面体，八面体（Octet），笼目（Kagome），虽然刚度和强度高，但结构屈服后易发生局部屈曲，导致应力急剧下降和剧烈波动，降低了能量吸收效率。而弯曲主导结构，如：体心立方结构（BCC），简单立方结构（SC），菱形十二面体结构（RD）[33-35]，虽然变形中应力平台稳定，但刚度和强度较低，导致结构承载能力较弱。如图 3(a)，(b)所示，为打破单一结构的性能瓶颈，将弯曲主导与拉伸主导的晶格结构相融合，在变形过程中，拉伸杆件单元以轴向变形为主，提供初始强度；而弯曲杆件单元在自身弯曲变形的同时还有效约束内部拉伸杆件单元的变形，可有效抑制不稳定屈曲，促进结构整体均匀变形。同时融合结构可改善单一的载荷传递路径，实现了应力平台更稳定和能量吸收更高效[36-39]。相较于单一晶格结构，异质晶格结构的平台应力提高约 11.1%，而比吸能（SEA）提高约 30%。

在此基础上，如图 3(c)所示，又延伸出了拉伸主导与扭转主导晶格融合。传统单一扭转结构在大变形下不稳定且几何设计受限。而受脱氧核糖核酸（DNA）结构启发将四螺旋手性单元(FHC)与 BCC 单元融合，可有效缓解这种缺陷，实现了压缩-扭转耦合，内部每个螺旋单元依次有序进入塑性变形阶段，空间螺旋手性单元的非对称扭转变形能力可提高结构的能量吸收，而 BCC 晶格框架确保了结构的整体稳定性[40]。Li 等人[41]选取 7 种代表性胞元，并通过整体互穿、体素交替、分层过渡和多尺度嵌入四种方式进行相互融合，比较了不同混合方式的优劣。其中，体素交替是将不同的点阵胞元按照特定规律在空间中交替排列，形成一种宏观上均匀但细观上周期性强弱变化的融合结构。在压缩过程中，相对较弱的胞元首先发生屈曲和变形，吸收能量；而较强胞元则保持刚度，提供支撑。这种强弱互补，顺序变形的机制使融合结构具有长而平稳的应力平台，最终极限强度提升 4 倍，总能量吸收提高 10%。

与静态载荷不同，冲击载荷的瞬时性和高能量会给结构带来灾难性的破坏。因此，HCSM 在冲击载荷工况下表现出更为优异的防护性能与应用价值。传统的立方体点阵具有优异的单轴压缩刚度，但端点处的铰接节点导致结构抵抗弯矩和剪切的能力较弱。而沿 z 方向增强的面心立方（FCCZ）结构节点刚性强，可有效弥补这种缺陷，结构在保证高刚度的同时还具备抵抗剪切和弯曲的能力。受到撞击时，力矩通过杆件更有效地在节点之间传递和分散，避免了局部失稳与应力集中[42]。此外，异质融合晶格还可以有效实现应力波调控与应变能储存。通过将承载性能好的全包围体心立方（GBCC）胞元与晶格能量吸收潜力大的 xy 双向包围体心立方（BCCxy）胞元交替排列，它们之间的阻抗差异导致应力波在层间界面处发生多次反射和透射，应力波传播速度降低了约 25%，延长冲击作用时间。同时不同胞元诱导的层级均匀变形顺序，还可以有效优化应变能存储路径，使结构的能量吸收提高 28.6%[43]。

传统桁架晶格结构在压缩载荷下易出现应力集中和剪切带问题，而板晶格结构则因压溃空间狭窄和制造缺陷导致机械性能提升有限。如图 3(d)所示，受深海玻璃海绵及竹子的启发，将板与桁架晶格融合设计。在冲击变形过程中，桁架部分率先屈曲，进而引发板晶格的协同弯曲和压缩。这种“分段”变形模式可有效抑制剪切带形成，促进渐进折叠，提升结构稳定性。同时板件与杆件分别通过形成塑性铰、以及弯曲与压缩变形，实现了高效的协同吸能[44,45]。

近些年，三周期极小曲面结构（TPMS）[46-48]因其优异的高比刚度，比强度及能量吸收特性逐渐成为多孔结构材料领域的研究热点。常见的 TPMS 结构如 IWP，Gyroid，diamond，Primitive 等都具有各自独特的力学特性（如 Gyroid 结构能量吸收效率高，而 IWP 结构承载能力较强）。为满足更复杂的应用工况及极端载荷条件，研究人员采用隐式函数（Sigmoid 函数

法[49]，高斯径向基函数 GRBF 法[50]）的方法实现不同 TPMS 结构之间的平滑过渡连接，设计出性能更优异的 HCSM。如图 3(e)所示通过将 SP-TPMS 结构（蓝色部分）与 Gyroid 结构（绿色部分）径向融合，组成了兼具高承载能力与高能量吸收的内外嵌套异质结构。在冲击载荷下，融合结构中不同 TPMS 胞元先后压溃，整体表现为层状渐进变形，有效抑制双剪切带形成，并实现多级能量吸收，最终异质 TPMS 结构相较于单一结构的平均压溃力（MCF）提高了 64.5%，压溃力效率（CFE）提高了 15.4%。且应变率越高，这种优势更明显，结构的抗冲击性和变形稳定性越好[51,52]。而将不同 TPMS 结构沿轴向融合时，通过调整融合顺序可实现结构力学响应的主动调控结构。当刚度较小的 TPMS 结构位于冲击端时，融合结构整体呈“渐进式”响应，初始应力平缓上升，随后逐步提高，利于长时段吸收能量；而当刚度较大结构位于冲击端时，融合结构呈“递减式”响应，初始应力急剧升高，随后因后端刚度较小部分被压实而产生应力下降，适用于抵抗瞬间极高冲击[53,54]。

当 TPMS 结构与传统桁架点阵融合时，克服了单一 SP-TPMS 结构载荷平稳但吸收能力弱、单一立方结构强度高但冲击峰值力过大的缺点。融合结构通过拓扑设计，巧妙地将两者的优势结合，在变形过程中，桁架结构与 TPMS 结构曲面交界处会产生附加扭转变形，这种杆-面间的相互作用有效分散了应力集中，避免了局部过早失效。同时应力通过融合结构实现均匀传递，降低了初始峰值力，提升了结构的韧性和能量吸收效率[55]。

1.1.2 蜂窝类

蜂窝结构是一种典型的二维多孔结构材料，被广泛应用于各类场景中。传统单一蜂窝结构（如常规六边形蜂窝）虽然具有轻质高强，缓冲吸能等优点，但在实际应用中也暴露出多方面缺陷，如薄壁易屈曲、节点薄弱、缺陷敏感等[56-58]。为提升蜂窝结构的性能，研究人员将一些简单的结构融入传统蜂窝设计中。如在蜂窝内部填充圆管(图 3(f))，外部蜂窝约束圆管的横向膨胀，内部圆管则对蜂窝壁板形成支撑，二者共同作用，形成更稳定的渐进折叠变形模式。同时，两者变形过程中的相互作用，引发更大程度的拉伸与扭转，从而显著提高结构的塑性变形能[59,60]。

随着对 HCSM 研究的不断深入，更丰富的拓扑构型设计开始出现。负泊松比结构[61-63]，因其独特的拉胀特性，使其具有许多优异的力学性能。如增强的的弹性模量与剪切模量[64,65]，更高的极限强度[66]及良好的抗冲击性[67,68]与能量吸收特性[69,70]。将六边形蜂窝与重入拉胀结构融合，其中六边形单元主要通过倾斜壁的弯曲承载载荷，而拉胀单元通过铰接机制（倾斜壁的旋转）吸收能量。同时，拉胀单元的负泊松比效应会抑制六边形单元的横向变形，促使结构整体发生均匀的层状屈曲，抑制局部剪切，相较于单一蜂窝结构，异质结构的塑性坍塌应力提升 16%，SEA 提升 38%[71]。

通常情况下，结构的泊松比在载荷下保持单一正值或负值，而将正泊松比特性的传统六边形蜂窝和负泊松比特性的凹圆弧蜂窝相结合（如图 3(g)），可实现独特的“弹性跳跃泊松比”效应。在动态压缩过程中，初期以传统六边形蜂窝部分为主导，泊松比呈正值；当应变达到阈值时，凹圆弧蜂窝开始参与变形，结构发生几何失稳，泊松比从正值跳跃到负值，结构变形由膨胀转为收缩。通过正负跳跃，结构不仅实现自适应调整变形行为，还优化了抗冲击和能量吸收性能[72]。而将负泊松比星型蜂窝与传统波纹结构融合可以有效实现结构在冲击载荷下的高刚度与强吸能相结合。波纹结构作为连续支撑体，其周期性褶皱提高了面内刚度和稳定性，防止局部屈曲。而星形蜂窝通过胞元的弯曲和拉伸变形吸收能量，并优化应力分布[73]。相同冲击载荷下，异质结构的后面板挠度下降 33.6%，这也为抗冲击夹芯结构的设计提供了新的思路。

1.2 增强型 HCSM

增强型异质结构主要的融合策略有两种，第一种是在简单构型中局部融合节点强化、杆件强化、板件强化，使得原本结构的承载力和吸能性能大幅提升；第二种是采取“强强联合”的策略，在单一型胞元中引入与其类型或性能相近的强化胞元，进而显著提升其特定性能。增强型 HCSM 重在优势性能的最大化开发与性能短板针对性提升。常见的增强型设计如图 4 所示。

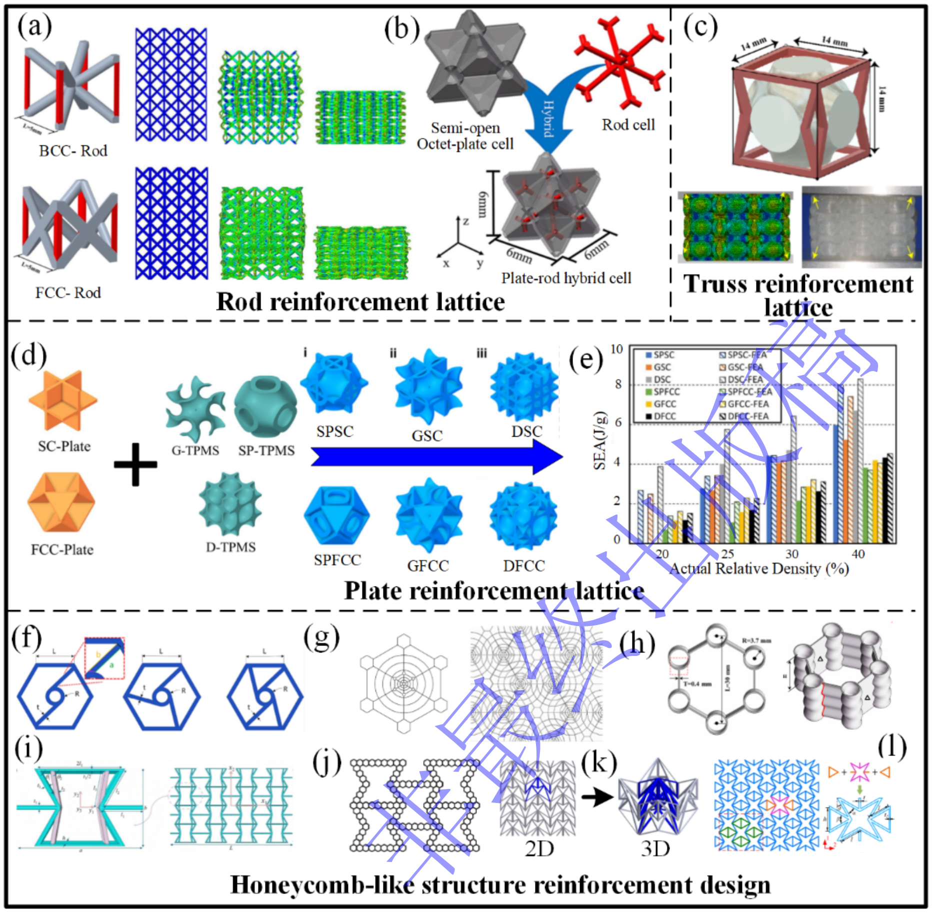

图 4.增强型 HCSMs: (a)BCC、FCC 晶格杆件增强及均匀变形模式[74] (b)Octet 板点阵内部杆件增强设计[75] (c)桁架与晶格融合设计[77] (d) 板点阵与 TPMS 晶格异质融合设计[79] (e) 不同相对密度异质结构 SEA 对比[79] (f) 不同韧带数异质手性蜂窝异质结构设计[86] (g) 蜂窝与蜘蛛网状加强筋异质融合设计[90] (h)蜂窝结构顶点替换异质设计[93] (i) 重入蜂窝结构加强肋设计[96] (j) 重入蜂窝结构边缘替换异质设计[106] (k) 斜柱填充设计与双箭头结构相融合[108] (l) 星型蜂窝异质结构设计[110-112]

Fig. 4 Enhanced HCSMs: (a) BCC and FCC lattice reinforcement with uniform deformation patterns [74]; (b) Reinforcement design of internal bars in Octet plate lattices [75]; (c) Truss-lattice fusion design [77]; (d) Heterogeneous fusion design combining plate lattices with TPMS lattices [79]; (e) Comparative energy absorption of heterogeneous structures with different relative densities [79]; (f) Design of chiral honeycomb heterogeneous structures with varying ligament numbers [86]; (g) Heterogeneous fusion design integrating honeycomb and spider-web reinforcement ribs [90]; (h) Heterogeneous design with vertex replacement in honeycomb structures [93]; (i) Reinforcement rib design for reentrant honeycomb structures [96]; (j) Edge replacement heterogeneous design for reentrant honeycomb structures [106]; (k) The Design of the Column Filling and the Double Arrow Structure[108] (l) Design of star-shaped honeycomb heterogeneous structures [110-112]

1.2.1 晶格类

最简单的异质晶格增强设计就是在传统晶格的基础上增加支撑杆件。杆件在变形过程中不仅能提供良好的支撑稳定作用还可以改善异质结构的变形模式。如图 4(a)，对于传统 BCC 与 FCC 等桁架晶格，杆件的增加使它们在压缩变形中不再因剪切带导致局部失效，而是转变为均匀的逐层压溃模式[74]。而对于 Octet 等板点阵如图 4(b)所示，内部填充杆件不仅约束了板的弯曲变形，还将变形起始位置从端面转移至层间。这一机制显著增强了结构在压溃时的整体稳定性[75,76]。

根据塑性铰理论，杆件的引入在增加有效塑性铰数量的同时，还形成了多路径能量耗散机制，从而显著提升了异质结构的能量吸收效率。相较于简单的杆件融合，定制化的桁架设计更适用于构型复杂、且追求多功能的晶格结构增强。如图 4(c)引入桁架不仅能填充晶格构型天然

存在的空隙，提高整体密实度，还能作为主要承载组件，在变形过程中有效分散应力集中并抑制局部屈曲，使结构的刚度提升 42%。此外，桁架与晶格的融合，使结构内部增加了大量的接触界面，在加载过程中，界面之间相互挤压作用，可以实现应力的高效分配与能量的多级耗散，相较于单一晶格结构，异质结构的的 SEA 提升 35% [77]。在此基础上，通过精准调控桁架与主体晶格的几何参数与融合方式，还可进一步实现减振、导热、抗冲击等性能的定制化设计，满足异质结构的多样化功能需求[78]。

对于性能优异，设计复杂的 TPMS 结构，如图 4(d)所示[79]，研究人员通常将板结构（如 SC 结构）与其进行融合增强。在该类融合结构中，板结构充当内部支撑骨架，负责提高整体结构的刚度和承载强度；而 TPMS 结构则起到“连接器”的作用，其特有的光滑曲面能够有效消除应力集中，从而实现更均匀的应力分布。在变形过程中，融合结构中的板区域会首先发生屈曲，但随后 TPMS 结构会抑制这种屈曲的局部化，迫使变形向更多层次发展，形成一种整体、渐进的坍塌模式。此外，在变形期间，板与曲面之间复杂的相互作用会引发压缩、拉伸和弯曲等多种变形机制，并促使更多塑性较的产生，从而在更高效抵抗外部载荷的同时，耗散更多能量（如图 4(e)），最终，与单一 TPMS 结构相比，异质结构提升巨大，其中刚度提高了 171%，强度提高了 125%，能量吸收提高了 117%。同时，通过板与 TPMS 几何对称性的巧妙组合，异质融合结构可以实现近乎各向同性的力学性能，使其适用于多轴负载的复杂工况[80-82]。

此外，将传统 BCC、SC 桁架点阵结构与 TPMS 结构进行融合设计时，TPMS 的连续曲面赋予结构良好的面内刚度与稳定性，而内部桁架杆件则提供了优异的轴向刚度和强度。在变形过程中，桁架能够有效分担载荷，并将高应力区从 TPMS 曲面区域转移至桁架杆件，从而实现了应力分布的重新优化。此外，融合结构还实现了优异的导热特性。其中具有巨大比表面积的 TPMS 结构，为对流换热创造了有利条件；而内部杆件能够引导流体形成特定的流动模式，促进流体的混合与换热过程[83]。

1.2.2 蜂窝类

通过在蜂窝结构中引入简单网格设计，可实现“骨架支撑”与“缓冲吸能”的功能分配与协同作用。在冲击载荷作用下，载荷能够沿着网格结构通过最短路径向周围高效传递，从而显著缓解因局部弯曲所引起的应力集中现象。蜂窝结构主要提供均匀的面外支撑刚度，并通过塑性压溃方式有效吸收冲击能量；在网格交叉点等关键部位，结构局部增强，有效抑制损伤的进一步扩展[84,85]。

传统蜂窝结构的能量吸收主要依赖于蜂窝壁的塑性屈曲与折叠，具有较为优越的能量耗散、冲击力衰减性能，但由于其结构主要由薄壁构成，其平台应力及整体能量吸收值相对较低。如图 4(f)，通过将手性单元与蜂窝结构有机结合，通过手性单元的节点旋转与韧带的弯曲变形，进一步增强了结构的能量耗散性能。同时，融合结构可以实现双平台协同承载机制，在压缩初期，第一阶段由蜂窝壁和手性韧带组成的复合结构承担载荷；当间隙被完全压实后，圆形节点自身开始直接参与承载，结构进入第二阶段，因此在中速冲击载荷下（20m/s）结构的 MCF 及 CFE 均提升 2 倍以上。此外，该机制使得结构在单次压缩过程中，依次经历两种不同且连续的能量吸收模式，从而显著延长了平台区，总能量吸收量最大提升约 138%[86,87]。除了引入简单的辅助结构，通过精妙的异质融合设计也可以有效增强蜂窝结构的性能。传统蜂窝结构因单元排列方式简单，往往存在应力集中和局部弱区等问题。采用自相似分形排列可以增强结构的拓扑连续性[88,89]，从而填补弱区并缓解应力集中现象。

如图 4(g)所示，结合蜘蛛网状加强筋，不仅能为蜂窝壁提供横向约束，抑制其过早屈曲，还能在结构内部形成复杂的载荷传递路径，使冲击能量更均匀地耗散[90,91]。受甲虫鞘翅启发，可将层级化设计策略引入蜂窝结构，采用多边形子结构分别替换蜂窝胞元的顶点与边缘。如图 4(h)，替换顶点可有效提高结构的局部刚度，在同等质量下，异质结构的 CFE 提升约 2.6 倍，并促进应力分布更加均匀[92,93]。而替换边缘则能引导结构整体变形模式由全局屈曲转向渐进式变形，同时形成分布更广泛的塑性应变集中区，从而激活更多塑性铰链，提高能量吸收效率，相较于传统蜂窝异质结构的能量吸收最高可提升约 7.5 倍[94]。如果在此基础上，继续引入梯度设计策略，将更多材料配置于高应变区域进行强化，可以进一步扩大塑性变形范围，实现能量

吸收性能的进一步提升[95]。

如图 4(i)，通过在经典负泊松比结构（重入蜂窝结构）中引入加强筋（肋）[96-101]，可显著提升其力学性能。加强肋可以增加结构的静定度，使其从结构状态转变为稳定状态，同时将变形模式从弯曲主导转向拉伸主导，从而大幅提升整体刚度与变形稳定性。此外，加强肋还能通过增加塑性铰链或提供额外支撑点，有效抑制局部屈曲，延长平台应力阶段，进而提升能量吸收效率。通过调整加强肋的方向与形状，还可进一步调控异质结构的泊松比和刚度，实现灵活的性能优化[102,103]。

在动态加载条件下，加强肋还有助于抑制惯性效应、延缓应力波传播，促进结构发生层序性坍塌，从而避免整体失稳，提升结构抗冲击性[104]。将重入蜂窝的倾斜胞壁替换为双圆弧壁或多边形胞元[105-107]（如图 4(j)），不仅能增加结构中塑性铰的数量，使能量吸收相最大提升约121%；还可以引入结构性分层，使得结构压溃过程变得有序。同时，这样的设计使结构在受压时具有更大的潜在横向收缩空间，表现出更显著的负泊松比效应。将重入蜂窝通过顶点重叠，如图 4(k)所示，斜柱填充设计后再与双箭头结构相融合，并利用 3D 互锁组装，构建出具有双向拉胀性和高结构完整性的空间拓扑异质构型。在压缩过程中，载荷由大量节点和支柱共同承担，避免了局部应力集中导致的过早失效，显著提升结构刚度，通过对比可知，新型异质结构相较于传统拉胀结构其归一化杨氏模量高出 20.65% 到 66.67% [108]。

传统星形负泊松比结构在面内压缩时，主要依赖斜臂的旋转与弯曲来耗散能量[109]。然而，由于其在变形过程中稳定性较差，容易发生整体弯曲，导致部分结构未能充分参与变形，从而过早进入密实化阶段。如图 4(l)，将其与双斜壁结构[110]，三角形结构[111]或圆形结构[112]等相融合[113]，可以实现异质结构的双阶段变形模式。其中第一阶段由星形结构的旋转主导，而第二阶段由融合结构整体的弯曲与压缩主导。这种分阶段的变形机制使得结构形成两端平缓、持久的应力平台，从而显著提高了总能量吸收效率。

2. 材料异质多孔结构材料

为了克服传统单一材料制备的多孔结构材料性能上方面的局限性，还可以通过一些功能材料进行辅助增强。如，泡沫材料和剪切增稠液等，将其与多孔结构材料进行填充融合，能够有效实现性能的调控与优化，从而制备出优异的 HCSM。

2.1 泡沫材料填充 HCSM

泡沫材料[114,115]由于它们的减震、缓冲、轻质、隔音和电绝缘、耐化学性和耐久性等有利特性，被广泛用于各种行业（例如建筑、运输、制冷、包装和家具工业等）。泡沫材料是一种具有高度非线性行为的固-气复合材料，其中聚合物固相被气相破坏，形成内部空腔。而内部空腔的密度和范围密切决定了泡沫材料的物理性能[116-118]。由于其多功能性，近年来，泡沫材料用作基质或填充材料在各种工程应用中得到了越来越多的关注[119-122]。

2.1.1 晶格类

通过自由发泡技术，可以将泡沫材料与晶格结构融合。如图 5(a)，(b)在变形过程中，晶格结构作为骨架提供刚性支撑，提升异质结构的整体强度；而粘弹性泡沫材料通过孔隙与气体的压缩机制耗散大量能量。此外，泡沫对晶格形成有效的侧向支撑，能够抑制其产生过早屈曲与应力集中，从而使结构的失效模式由脆性断裂变为渐进式压溃[122-124]。在动态冲击载荷下，泡沫材料可延缓冲击波的传播，使晶格更充分的发挥其塑性变形能力，延长能量吸收过程。如图 5(c)所示，在泡沫与晶格的接触界面，物理结合增强了界面摩擦和机械互锁作用，晶格支柱断裂后不会产生四散飞溅，而是被泡沫束缚在原位，继续参与能量耗散[125,126]。

除了发泡技术外，还可借助增材制造技术，在晶格制造过程中将泡沫材料注入其内部，实现二者的有效融合。如图 5(d)，利用打印机的双挤出系统，研究人员设计了一种聚氨酯泡沫注入工艺，用于填充空腔的海胆（SU）晶格结构。在循环加载条件下，异质结构相较于等重量的空结构不仅刚度和能量吸收分别提升约 60%与 102%，同时比阻尼容量高出约 50%，具备良好的减振效果（图 5(e)）。主要归因于内部填充的泡沫材料兼具粘弹性和多孔特性，可作为高效阻尼介质，将振动能迅速转化为热能，从而适用于振动控制领域[127]。

此外，A.Corvi 等人[128]通过在打印代码中设置暂停点，在打印即将完成前向 TPMS 晶格（Schwarz Primitive）中注入聚氨酯泡沫，然后继续打印顶层，确保良好粘合。泡沫填充异质结构在压缩过程中的应力分布更均匀，减少了梯度效应。晶格外壳的变形由弯曲主导转变为压缩主导，减少了应力奇点。在循环加载中，得益于泡沫的超弹性迟滞特性及结构更规则的变形，融合结构的比阻尼容量及能量耗散也大幅提高。这也进一步体现了 HCSM 设计的巨大潜力。

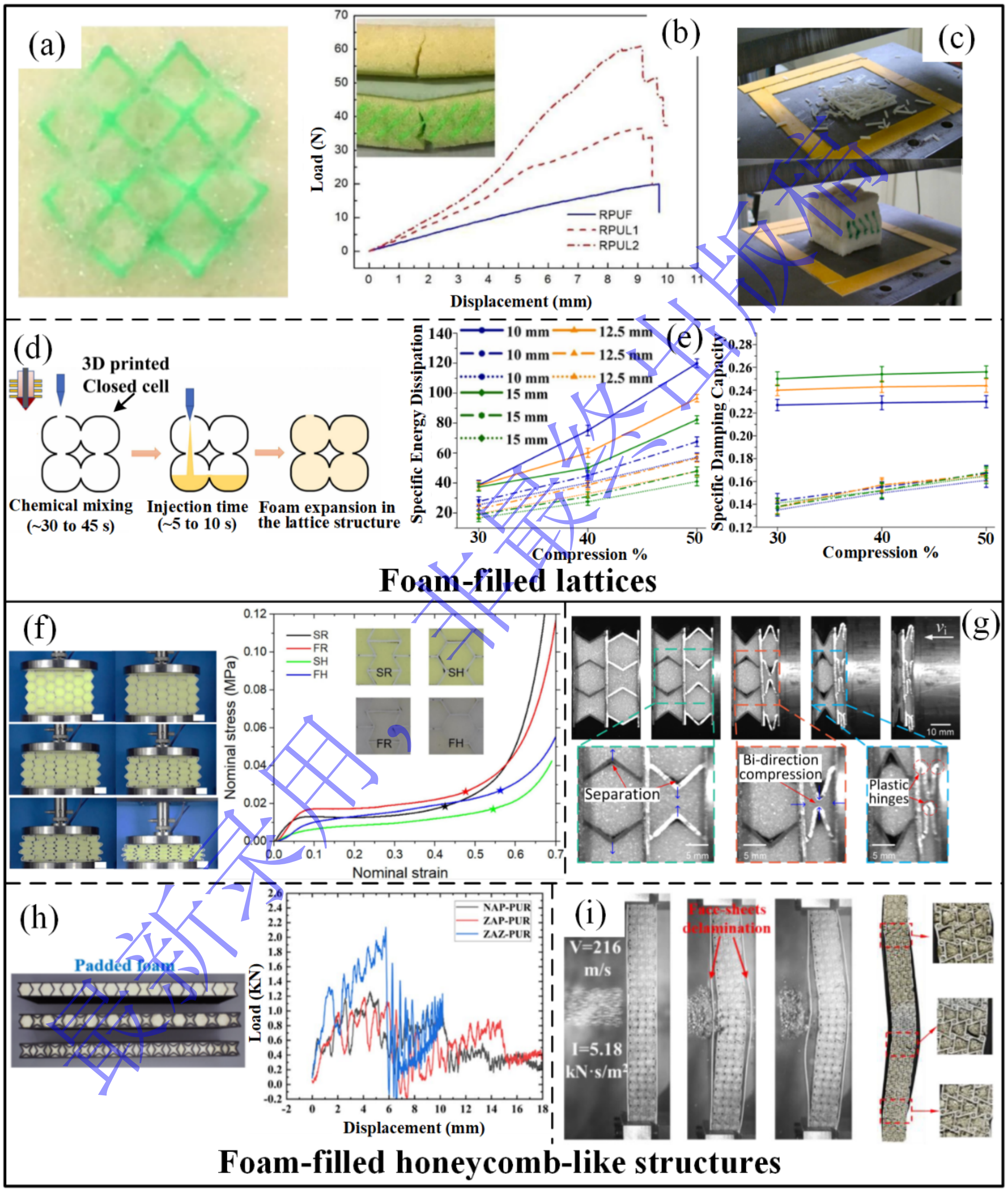

图 5.泡沫材料填充 HCSMs：(a)晶格结构泡沫发泡制造过程[124] (b)泡沫材料填充 HCSMs 的载荷位移曲线及断裂行为[124] (c)泡沫对晶格杆件的有效束缚[125] (d) 增材制造聚氨酯泡沫填充工艺[127] (e)异质结构优异的减振、吸能对比[127] (f)泡沫填充六边形蜂窝[135] (g)泡沫填充负泊松比结构的抗冲击吸能特性[136] (h)内凹蜂窝结构，六边形蜂窝结构及零泊松比星型结构泡沫填充结构优异抗冲击特性[145] (i)聚氨酯泡沫填充混合手性结构的局部抗冲击动态响应过程[148]

Fig.5 Foam filled HCSMs: (a) Lattice-structured foam fabrication process [124] (b) Load-displacement curves and fracture behavior of foam filled HCSMs[124] (c) Effective confinement of lattice members by foam [125] (d) Additive manufacturing of polyurethane foam fillers [127] (e) Superior vibration damping and energy absorption performance of heterogeneous structures [127] (f) Foam-filled hexagonal honeycomb [135] (g) Impact energy absorption characteristics of foam-filled negative Poisson's ratio structures [136] (h) Outstanding impact resistance of foam-filled structures including concave honeycomb, hexagonal honeycomb, and zero Poisson's ratio star-shaped configurations [145] (i) Local dynamic response of polyurethane foam-filled hybrid chiral structures under impact [148]

2. 1. 2 蜂窝类

相较于三维晶格材料，研究人员通常更倾向于将泡沫材料与二维蜂窝类结构融合[129-134]。压缩变形过程中，蜂窝框架与泡沫填充材料协同承载。如图 5(f)，载荷首先由刚度较大的蜂窝框架承担，随着框架变形，应力逐渐传递给内部的泡沫。泡沫除了自身的压缩，还可以为蜂窝提供侧向约束，防止蜂窝壁过早地屈曲塌陷导致整体结构的失稳，整个压缩过程融合结构应力分布均匀，具有良好的承载能力与能量吸收能力[135]。而对于重入蜂窝结构，如图 5(g)，在泡沫的侧向约束下结构的负泊松比特性可以更好地展现，相较于空结构，填充结构的峰值应力与平台应力分别提升 27.3%与 34.5%；而这种拉胀特性也使内部泡沫受到加载方向及横向收缩两个方向的挤压，压缩更加充分，吸收更多的能量[136]。

将泡沫材料填充到夹芯结构的蜂窝芯层中，能够显著提升结构的抗冲击性能。一方面，泡沫材料增强了芯层与面板的粘结效果，抑制了界面剥离的发生，使冲击波传递更均匀，避免形成应力集中。另一方面，变形过程中泡沫与蜂窝之间的相互作用增强，表现出明显的应变率强化效应和高能量吸收能力，从而更有效地抵御冲击载荷[137,138]。

还有一些研究人员将特殊设计的蜂窝结构与泡沫材料相融合，探究泡沫与结构的相互作用机理与增强效应[139-144]。如图 5(h)，将负泊松比重入蜂窝结构，正泊松比六边形蜂窝结构及零泊松比星型结构相互结合，同时填充聚氨酯泡沫材料，组成创新的异质结构设计。在冲击载荷下，未填充结构的损伤往往高度集中于冲击点正下方，极易发生穿孔破坏。而填充结构的泡沫材料通过优化应力传递路径，将局部化的冲击损伤分散至更多结构胞元共同承担，实现了局部强化，最终显著减小正面冲击形成的孔洞半径，并有效抑制边缘撕裂与局部压溃现象[145]。Chen 等人[146]研究了聚氨酯泡沫填充对双箭头结构抗爆性能的影响。结果显示，泡沫填充使结构后面板挠度显著降低了 48.2%，破孔面积减少了 19.2%，还有效改善了结构的失效模式，抑制了界面脱粘和局部冲击等不利现象。

与单纯通过增加金属用量来增强结构相比，泡沫填充是一种更具性价比和效率的优化策略。在手性结构与泡沫填充介质结合的体系中[147-149]，泡沫通过物理支撑约束手性单元的侧向变形，从而降低高变形区的应力集中，延缓裂纹产生。泡沫的柔韧性使其能顺应手性单元的变形并填充空隙，形成连续介质以优化载荷传递路径。如图 5(i)所示，手性结构的负泊松比效应与泡沫的多向压缩响应相互耦合，形成“锁紧”机制，使能量通过泡沫致密化与单元壁塑性变形进行耗散。同时，泡沫作为牺牲材料，可通过界面脱粘等可控失效形式进一步吸收能量，减少主体结构的损伤，最终提升异质结构的韧性与耐久性。然而，泡沫填充也带来一定问题，过强的约束与刚化效应会导致结构趋于脆性，使其塑性变形能力受限，表现为达到峰值载荷后承载力急剧下降，进而缩短了有效的吸能行程。因此，在设计时需考虑蜂窝构型、泡沫属性与载荷条件的匹配，以最大化协同效应，避免负面作用。

2. 2 剪切增稠材料填充 HCSM

采用轻质材料填充多孔结构材料已被证实是增强结构抗冲击性与能量吸收能力的有效策略。剪切增稠材料（STF/STG）作为一种智能材料[150,151]，具有独特的流变行为：在外加载荷作用下，其粘度迅速增大，呈现剪切增稠特性；而载荷移除后，材料又恢复至低粘度状态，表现出剪切稀化行为[152-154]。因此，该类材料在常态下保持柔软，而在冲击过程中则迅速硬化[155-157]。同时，其粘性耗散机制赋予材料显著的可逆能量吸收能力[158,159]。基于上述优势，剪切增稠材料也已成为冲击防护领域的研究热点。

2.2.1 STF 填充

Clark 等人[160]最先将 STF 引入规则蜂窝结构中，并指出填充剪切增稠液可以显著降低蜂窝结构冲击端部的损伤，同时增加结构的能量吸收能力。后续研究人员又对蜂窝填充 STF 进行了各类动态测试实验，并总结增强机理与规律。如图 6(a)，(b)在高速冲击瞬间，剧烈的动态变形使 STF 局部剪切率超过临界值，触发剪切增稠效应，其粘度急剧上升，从而对蜂窝单元壁施加

显著的流动阻力。这一作用延缓了蜂窝的塑性屈曲与压溃，进而提升结构的整体刚度与能量吸收能力。同时，如图 6(c) STF 通过提供有效的侧向支撑，促进结构变形均匀化，进一步抑制局部屈曲和剪切带的形成[161,162]。而将 STF 填充于负泊松比结构内，可实现二者智能响应的耦合。如图 6(d)，以 STF 填充的星形蜂窝为例，在冲击载荷下，结构的负泊松比效应引发面内收缩，从而在局部产生高强度剪切场。该剪切场大幅提高 STF 的剪切应变率，触发其剪切增稠效应，增强局部稳定性，延缓结构失效，使其在更高冲击速度下保持整体完整。同时，STF 填充约束了约 82%胞元的面内旋转行为，促使变形机制从旋转主导转为收缩主导（图 6(e)），MCF 提升 253%，从而进一步提升结构的能量吸收效率[163]。

将 STF 填充入空腔晶格结构，STF 的相变与晶格结构变形相互促进，形成正反馈。STF 的剪切增稠效应相当于在晶格结构的关键变形区域内部生成了临时的加强筋，极大地增强了该区域的局部刚度和强度，有效抑制了结构的进一步屈曲或失稳。如图 6(f)，相较于空结构，其峰值力降低 58%，而能量吸收提升 85%[164]。虽然 STF 填充对结构抗冲击性能的提高有显著作用，在航天防护等领域具有广泛应用潜力，但其在制备过程中会受到材料成分占比，温度等的影响[165]，同时填充结构的形状，壁厚也会直接影响最终的耦合过程。因此未来该类异质结构的制备还需要更精细的设计与参数调控。

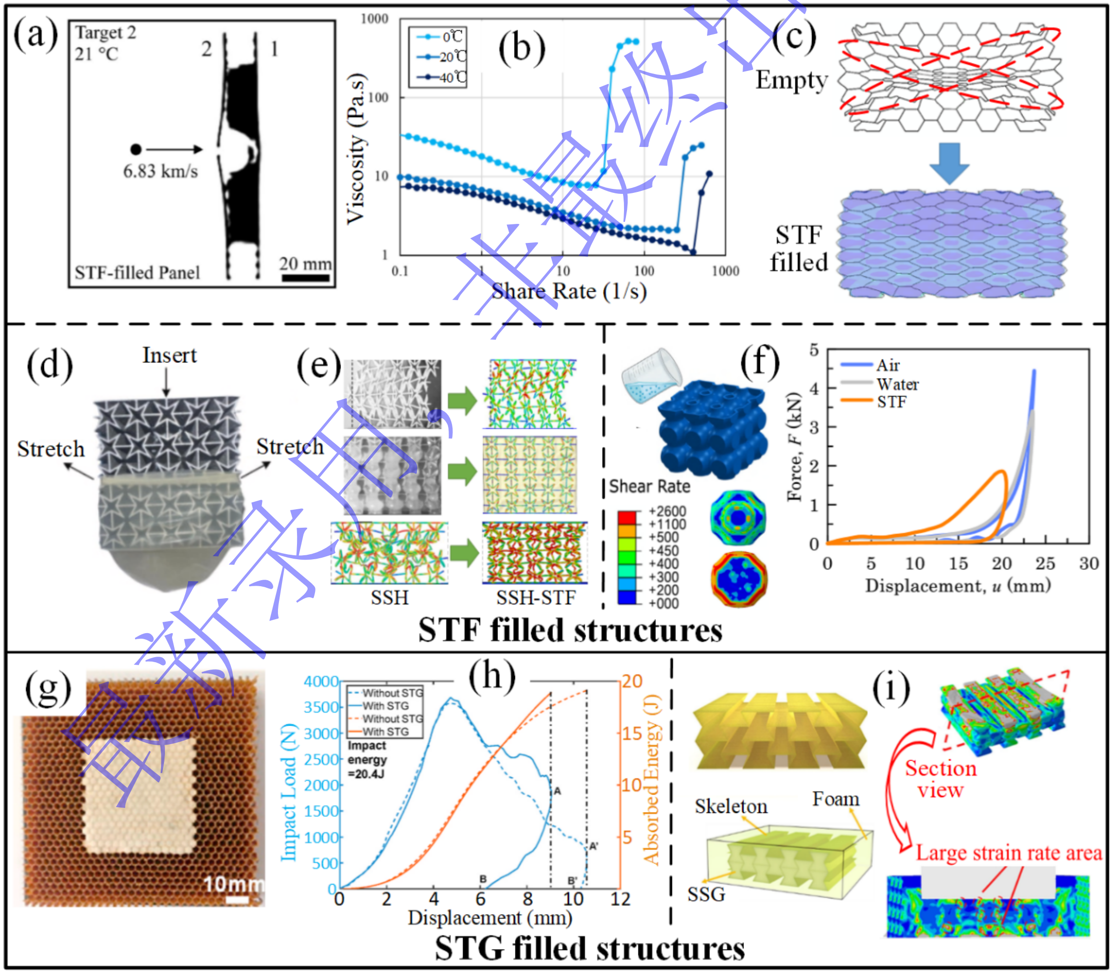

图 6.剪切增稠材料填充 HCSMs：(a)STF 填充蜂窝结构 2D 扫描图[161] (b)STF 剪切增稠速率[161] (c)蜂窝结构填充 STF 后均匀的变形模式[162] (d)STF 填充星型蜂窝结构示意图[163] (e)STF 填充星型蜂窝结构与未填充结构变形模态对比[163] (f)STF，水，空气填充空腔晶格结构的位移-载荷曲线对比[164] (g)STG 填充六边形蜂窝结构示意图[170] (h)STG 填充结构与未填充结构力-位移曲线对比[170] (i)负泊松比结构填充 STG 后的冲击响应示意图[171]

Fig.6 Shear-thickening material filled HCSMs: (a) 2D scanning image of STF-filled honeycomb structure [161] (b) STF shear-thickening rate[161] (c) Uniform deformation pattern of honeycomb structure after STF filling [162] (d) Schematic diagram of STF-filled star-shaped honeycomb structure [163] (e) Comparative deformation modes of STF-filled star-shaped honeycomb structure versus unfilled structure [163] (f) Displacement-load curve comparison of STF, water, and air-filled cavity lattice structures [164] (g) Schematic diagram of STG-filled hexagonal honeycomb structure [170] (h) Force-displacement curve comparison of STG-filled structure versus unfilled structure [170] (i) Impact response schematic of STG-filled negative Poisson's ratio structure [171]

2.2.2 STG 填充

基于悬浮系统的 STF 通常具有诸如挥发性、颗粒沉降、难以储存和飞溅等缺点，从而损害其耐久性、稳定性、可运输性和二次冲击抗性。为了解决这些问题，提出了基于聚合物体系的剪切增稠凝胶（STG）[166-168]。与 STF 相比，STG 通常具有较高的初始模量、初始粘度和较好的稳定性，在自然状态下，STG 通常表现出半固体性质，克服了 STF 易挥发、颗粒沉降和不易储存的缺点[169]。与 STF 的增强机制类似，将 STG 填充蜂窝结构也可有效增强结构的抗冲击性能。蜂窝骨架为 STG 提供了约束和力的传导路径。当冲击点作用于面板时，面板将集中力分散到下方的多个蜂窝单元。如图 6(g)，(h) STG 在单元内被压缩，激发出剪切增稠效应，并将应力更有效地传递给蜂窝壁，进而传递到整个结构，使更大范围的材料参与抗冲击。同时，这改变了结构的失效模式，从逐层失效变为整体协同承载，从而使侵彻深度降低了 14.3%，能量吸收总量提高了约 6.1%[170]。

对于负泊松比填充结构[171]，如图 6(i) 受压时结构产生拉胀效应，导致内部出现高应变率集中区，这些区域内的 STG 被迅速激发而“固化”，率先承担载荷；同时，低应变率区域的 STG 仍保持流动性，允许大变形以横向耗散应力，这种“部分固化、部分流动”的模式，实现了结构优异的抗侵彻性能，同时相较于未填充结构，其能量吸收增长约 60%。

除此之外，通过在 STG 中加入不同的功能材料，还可以实现拓展的应用。如将磁性颗粒（如片状羰基铁粉）掺入 STG 中形成磁性 STG，填入蜂窝结构后，组成典型的吸波结构。蜂窝的周期性结构本身会引起电磁波散射和共振，增强吸收，而 STG 中磁性颗粒通过磁滞损耗、涡流损耗等多机制将电磁能转化为热能消耗掉，最终实现宽带吸收[172]。

3. 面临的挑战及未来发展方向

3.1 连结性问题

当不同多孔结构材料进行融合设计过程中，为了保证不同拓扑单胞间平滑的连接及载荷良好的传递，结构与结构间的连接性问题就尤为重要。有些融合晶格结构在设计时，通过确保两种单胞在界面处具有几何兼容性，即连接位置的节点数量与空间位置一致，可使不同晶格的杆件在界面处共享节点[173]。此种设计实现了结构间的自然过渡，无需任何额外连接介质。但大多数结构在融合过程中需要通过策略性地调整节点的连接位置[36]，或增加杆件[38]、板件[174]、边框[175]等媒介来保证连接性。然而，增加额外的连接介质不仅增加结构的整体重量，也有导致结构完整性被破坏的风险。此外，对于特殊的 TPMS 结构，传统的连接方式已无法满足，寻求完美的数学过渡方程或拓扑优化方法也仍待更深入的研究[176-178]。因此，结构的连接设计及优化是未来 HCSM 研究的重要方向。

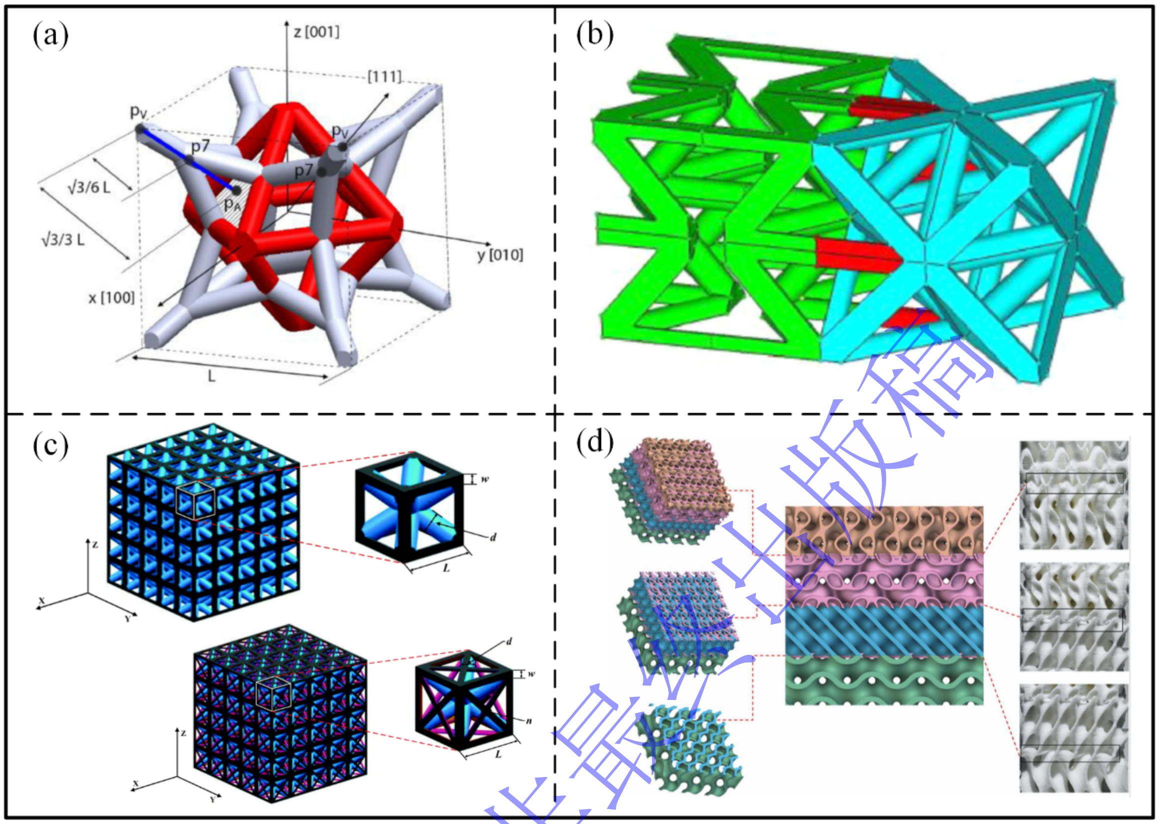

图 7. HCSMs 的连结性问题：(a)Octet 结构与 BCC 结构融合中的节点调整策略[36] (b)Octet 结构与 MOD 结构的杆件连接[38] (c)异质晶格结构的框架连接[175] (d)不同 TPMS 结构之间的融合界面[178]

Fig.7 Connectivity issues of HCSMs: (a) Node adjustment strategy for fusion of Octet and BCC structures [36]; (b) Rod connections between Octet and MOD structures [38]; (c) Framework connections in heterogeneous lattice structures [175]; (d) Fusion interfaces between different TPMS structures [178]

3. 2 增材制造工艺的影响

HCSM 的复杂性对其制造过程提出了严峻挑战[179,180]。由于在材料组成和几何构型上存在显著差异，单一制造方法及工艺参数往往难以直接适用于异质多孔构件。特别是在涉及多材料、多尺度构型融合的情况下，诸如界面结合强度、材料间热膨胀系数失配以及结合相容性等问题，均对制造工艺的选择与流程设计构成重要制约。若不能在制造技术方面实现创新并推进工艺精细化，易导致构件出现局部缺陷或整体性能偏离设计目标，影响结构的可靠性。因此，未来研究可以重点关注本文提到的泡沫填充、剪切增稠材料灌注与金属/聚合物多孔骨架的结合，深入研究异质材料在增材制造过程中的界面形成机理。探索如何通过工艺参数（如能量输入、铺粉/挤出力）调控，实现从机械互锁到冶金/化学结合的界面强化，以解决界面结合强度不足和热应力失配的核心难题。此外， 在 HCSM 的生成设计阶段，提前嵌入制造约束（如最小特征尺寸、最大悬垂角度等约束）可以有效保障 HCSM 的制造精度。同时可以开发适用于 HCSM 制造的在线监测技术，如高速摄像、热成像等，实时捕捉制造缺陷（如杆件断裂、填充不匀、界面分层等）。基于监测数据构建实时反馈系统，动态调整工艺参数，实现制造过程的闭环质量控制，确保复杂 HCSM 性能的一致性[181]。

3. 3 性能验证与数值模拟工作的复杂性

当前关于 HCSM 的研究，仍多聚焦于准静态单轴压缩等简单加载条件。然而，作为具备优异性能的结构材料，HCSM 在实际工程应用中常面临冲击、疲劳、爆炸、多轴压缩等多种复杂载荷工况[11,182]。因此，有必要对其在更为接近真实服役环境下的力学行为展开系统性测试与评估。该工作涉及多类载荷条件与结构响应之间的耦合关系，无疑是一项复杂而具挑战性的任务[183,184]。这进一步需要针对不同结构形式设计相应的实验方法，并建立完善、严谨的性能评价

指标体系。

有限元数值模拟是研究 HCSM 力学性能及其内在机理的有效手段。然而，在处理复杂的非线性问题或多尺度问题时，基于传统商业软件的结构建模与分析常面临计算效率低下和结果精度不足的挑战[185,186]。尤其对于具有复杂几何构型的结构，如异质三周期极小曲面结构，为保证模型及计算精度，其网格划分往往导致庞大的单元数量，这进一步加剧了数值模拟在计算效率上的压力。因此，未来应重点关注高阶单元、多尺度计算方法与并行计算框架的融合，提升对复杂非线性行为与跨尺度力学响应的解析效率。此外，通过结合增材制造等先进制备工艺，发展“设计-模拟-制造”一体化集成平台，实现从几何建模到性能预测的高效闭环，为复杂的 HCSM 提供更智能、更精准的仿真解决方案。

3.4 多功能实现的瓶颈

HCSM 因其能将多种优异性能集成于一体而展现出显著优势。然而，要在实际应用中充分发挥其潜力，仍需对其多物理场耦合机制与微结构设计进行更深层次的理论探索与实验研究。特别是在多功能集成场景下，如何在一个复杂的结构设计中协同实现高导热性、优良导电性、高效隔音性以及出色的减振性能，仍是一个极具挑战性的科学问题[187,188]。基于本文所述，可以进行拓扑构型对多功能性的定向调控研究，利用 TPMS 结构、手性结构等特殊拓扑在应力传递、流体通道、波传播等方面的先天优势，进行有针对性的融合设计。如梯度异质 TPMS 结构，其内部梯度变化不仅可以优化冲击能量的吸收路径，同时其连续光滑的曲面特性能够有效引导冷却流体，实现“冲击防护-主动散热”的一体化。此外，基于材料异质策略（STF/STG 填充、泡沫填充），深入研究其流变学、热力学与结构力学之间的耦合机制。在探索剪切增稠材料在冲击下固化的同时，其导热/导电性能的协同变化规律，可以为开发兼具抗冲击、传感与热管理功能的智能防护材料提供理论依据。因此，突破现有单一功能优化的设计范式，揭示多物理性能之间的耦合规律，是下一步研究的重点，也是实现此类材料在高端装备、航空航天及电子器件等领域创新应用的关键。

3.5 人工智能与机器学习的深度融合

人工智能为 HCSM 设计提供了突破性工具，显著拓展了设计自由度[189,190]与性能优化能力。如图 8 所示，首先基于人工智能的生成设计方法能够自主创制高性能拓扑构型，实现结构轻量化与功能最大化[191-193]；其次，机器学习模型可快速准确预测结构在复杂工况下的力学行为与失效模式，大幅降低计算成本[194]。此外，人工智能支持以性能目标为导向的逆向设计，通过优化算法[195-197]在广阔设计空间中搜索符合特定需求的结构构型。

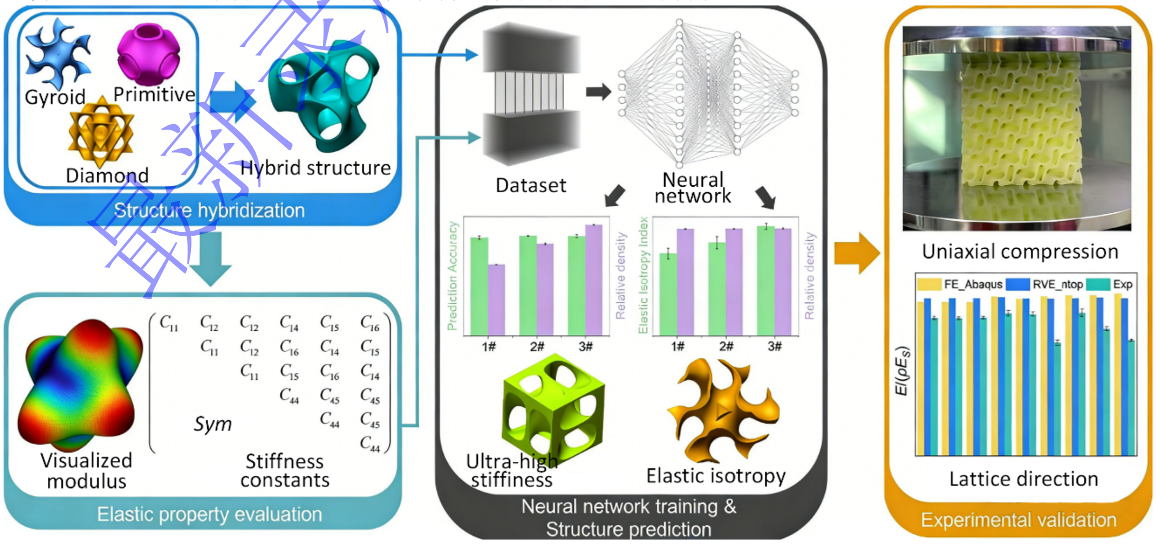

图 8. 通过机器学习进行异质多孔结构材料设计框架[193]

Fig.8 Machine Learning-Based Framework for Heterogeneous cellular Structure Design [193]

然而，该领域仍面临突出挑战：现有算法在极端工况下的预测精度与鲁棒性尚需提升，且

人工智能生成的结构往往几何复杂，超出当前制造工艺可实现范围，导致“可设计不可制造”困境。为此，未来研究重点构建集成“性能需求-材料选择-工艺参数”的端到端机器学习模型。该框架以目标性能（如特定冲击速度下的峰值力、能量吸收量）为输入，逆向推荐可行的异质构型（如互补型晶格组合、泡沫填充方案）及对应的增材制造工艺参数，并将制造约束嵌入生成设计过程，直接解决设计-制造之间的矛盾。此外，利用目前已有的关于 HCSM 的实验与仿真数据（如各类异质结构的应力-应变曲线、变形失效模式等），训练高精度的图神经网络（GNN）或深度学习代理模型。这些模型能够近乎实时地预测新型 HCSM 在爆炸、多向冲击等复杂载荷下的动态响应，极大加速新材料的筛选与性能评估流程。同时，开发适用于 HCSM 的多目标强化学习或贝叶斯优化算法。在同时考虑轻量化、抗冲击性、导热性、减振性等多个优化目标时，算法能在广阔的异质设计空间中进行高效探索，自动寻找到帕累托最优解集，为多功能 HCSM 的设计提供直接指导。

4 结　论

HCSM 凭借拓扑构型与材料的创新性功能融合，突破了传统单一均质多孔结构材料在抗冲击性能上的固有瓶颈，已成为轻质高强冲击防护材料领域的核心研究方向。本文从拓扑构型异质与材料异质两大维度，系统梳理了互补型、增强型异质晶格/蜂窝结构，以及泡沫、剪切增稠材料填充的材料异质结构的设计策略与抗冲击增强机理，明确了多结构协同、多材料耦合、多机制耗散是 HCSM 实现能量吸收效率、刚度与稳定性同步提升的核心逻辑。

拓扑构型异质通过拉伸−弯曲/扭转主导结构的融合、TPMS 结构的多维度复合、正负泊松比结构的协同设计等方式，实现了载荷传递路径的优化与变形模式的精准调控，有效抑制了局部屈曲、应力集中与剪切带形成；材料异质则依托泡沫材料的侧向约束与粘弹性耗散、剪切增稠材料的冲击响应型硬化特性，与多孔基体形成强耦合效应，进一步强化了结构的渐进式变形与多级能量吸收能力。两类异质结构材料的设计均通过“功能互补−性能增强”的协同机制，使结构兼顾轻量化与高抗冲击性，为航空航天、汽车安全、生物医学等领域的防护装备设计提供了多元化解决方案。

当前 HCSM 的研究虽已取得显著进展，但从实验室设计走向工程化应用，仍面临诸多关键挑战：拓扑构型融合中的界面连接性优化问题尚未得到彻底解决，额外连接介质易导致结构增重与完整性受损；增材制造工艺与异质结构的多材料、多尺度特性匹配度不足，界面结合强度、热膨胀失配等问题影响构件性能可靠性；现有性能验证多局限于准静态单轴压缩，复杂工况下的力学行为与失效机制研究仍不充分；多物理场耦合下的多功能集成设计缺乏系统的理论支撑，难以同时实现抗冲击、导热、减振等多元性能需求。

尽管如此，HCSM 的发展前景依然广阔。人工智能与机器学习技术的深度融合，为解决上述难题提供了突破性路径——生成式设计可自主创制高性能拓扑构型，机器学习模型能快速预测复杂工况下的结构响应，“设计−模拟−制造”一体化智能框架则有望破解“可设计不可制造”的困境。未来，围绕连接性优化的拓扑设计、多材料兼容的增材制造工艺、复杂工况的性能评价体系、多物理场耦合的多功能集成四大方向，结合仿生设计、多尺度计算等前沿技术，HCSM 将实现从性能提升到功能定制的跨越。

综上所述，HCSM 凭借其独特的功能融合与协同增强优势，成为新一代高性能冲击防护材料的核心发展方向。随着设计理论的完善、制造技术的创新与智能算法的赋能，HCSM 将在航空航天超轻质防护、高端汽车抗撞设计、柔性人体防护装备等领域实现规模化工程应用，为现代工程对轻量化、高强度、多功能一体化防护的严苛需求提供全新解决方案，推动冲击防护材料领域的技术革新与产业升级。

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Research Progress on Design Strategies and Impact Resistance of Heterogeneous Cellular Structures Material

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Abstract: As lightweight and high-strength functional-structural integrated materials, cellular structural materials are widely applied in aerospace, automotive manufacturing, and biomedical fields. However, traditional single-configuration cellular materials (e.g., honeycomb structures and point-lattice lattices) gradually exhibit performance limitations under complex conditions such as impact shock waves, multi-directional impacts, or nonlinear deformations. Against this backdrop, Heterogeneous Cellular Structure Material (HCSM) have emerged as a research hot pot in impact protection. This paper systematically reviews recent design strategies and impact resistance performance of HCSM. HCSMs are primarily categorized into two types: topological configuration heterogeneity (including complementary and enhanced fusion) and material heterogeneity (e.g., filling with foam materials and shear-thickening materials). Through innovative "functional fusion" approaches, they overcome the performance bottlenecks of single-configuration cellular materials. The study further elucidates the synergistic reinforcement effects and deformation mechanisms of HCSM under impact loads, while analyzing their intrinsic mechanisms for improving energy absorption efficiency, stiffness, and stability. Despite significant progress in HCSM research, challenges remain in connectivity optimization, additive manufacturing process compatibility, complex condition validation, and multifunctional integration. Going forward, the integration of artificial intelligence and machine learning technologies holds promise for achieving end-to-end optimization of HCSMs from design to manufacturing, thereby providing new directions for developing next-generation high-performance impact-resistant structural materials.

Keywords: heterogeneous cellular structure material; impact resistance; design strategy; functional integration; energy absorption