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多物理场耦合的可编程超材料研究进展

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摘　要：为系统总结可编程多物理耦合超材料的理论基础、设计方法、制造路径及工程化进展，明确当前研究中的关键科学问题与发展趋势，文中在梳理多学科交叉背景的基础上，提出了一种以“理论–设计–制造–表征–应用–工程化”为核心主线的系统性研究框架，旨在为按需功能化与智能响应型超材料的设计提供理论依据与工程指导。首先，从等效介质与均匀化理论出发，阐述了 Bloch 波与拓扑物态在超材料建模中的作用机制，结合非线性多稳态分析与物理约束机器学习，探讨数据驱动与物理驱动相融合的建模思路。其次，比较拓扑优化、贝叶斯优化、强化学习与生成式模型等前沿设计范式，提出在超材料设计阶段应显式引入可制造性约束与容差鲁棒性评估。然后，系统总结了从微纳到宏观的增材制造与 4D 打印技术路线，并分析多材料与时变结构在可编程超材料中的实现策略。最后，构建跨域性能表征指标体系与标准化流程，提出基于数据同化与参数反演的综合评价框架。研究结果表明，当前超材料研究正从单一性能的奇异发现，迈向多场耦合、可重构与可编程的系统化设计。通过融合智能优化与增材制造，超材料在隔振与能量吸收、吸波与隐身、声聚焦与降噪、热管理、柔性传感与生物医用，以及航天轻量化等领域实现了性能突破与原型验证。文中总结的研究体系为超材料的功能可编程设计提供了可推广的技术路线，并指出未来发展应聚焦于多尺度耦合机理、制造精度控制、可靠性评估与工程规模化集成，以实现超材料从实验室走向实用工程的关键跨越。

关键词：超材料；可编程结构；拓扑优化；4D 打印；多物理耦合

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Research progress of multiphysical coupled programmable metamaterials

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Abstract: To systematically summarize the theoretical foundations, design methodologies, fabrication strategies, and engineering translation of multiphysical coupled programmable metamaterials, and to elucidate the key scientific questions and emerging trends in current research, this review proposes an integrated research framework that connects “theory-design-manufacturing-characterization-application-engineering”. The framework aims to provide a solid theoretical insights and engineering guidance for the on-demand functional design and intelligent responsiveness of metamaterials. Based on effective-medium and homogenization theories, we elucidate the modeling principles of Bloch-wave analysis and topological phases, and discuss the integration of nonlinear multistability with physics-constrained machine learning to achieve hybrid data-physics-driven modeling. Furthermore, we compare advanced design paradigms, such as topology optimization, Bayesian optimization, reinforcement learning, and generative modeling, and highlight the importance of explicitly incorporating manufacturability constraints and tolerance robustness at the design stage. Subsequently, the development routes of additive manufacturing and 4D printing from micro/nano to macro scales are summarized, together with multi-material and time-varying programmable strategies. Finally, cross-domain characterization metrics and standardized protocols are consolidated, and a unified framework is proposed based on data assimilation and parameter inversion. The study reveals that metamaterials research is evolving from the discovery of isolated exotic properties toward integrated, reconfigurable, and programmable multifunctionality. By integrating intelligent optimization and additive manufacturing, metamaterials have achieved remarkable performance enhancements and prototype demonstrations in vibration isolation, energy absorption, electromagnetic absorption and cloaking, acoustic focusing and noise

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control, thermal management, flexible sensing, biomedical applications, and lightweight aerospace systems. The proposed framework provides a generalizable technical roadmap for functional design and engineering translation of programmable metamaterials. Future research should focus on understanding multiscale coupling mechanisms, improving fabrication precision, enhancing reliability evaluation, and promoting system-level integration to bridge the gap between laboratory demonstrations and real-world engineering applications.

Keywords: metamaterials; programmable architectures; topology optimization; 4D printing; multiphysics coupling

超材料(metamaterials)的提出为传统材料科学与工程学科注入了全新的设计思路和理论框架[1-8]。与依赖材料本征属性来获得性能的传统材料不同，超材料通过人工设计的几何构型、周期或准周期排列以及跨尺度的结构组织，在宏观尺度上展现出自然界中难以实现甚至不存在的等效物性[9-14]。这一核心思想使得研究人员能够在不改变材料本身化学组成的前提下，通过结构单元的拓扑、尺寸、层级以及排列方式来实现包括负折射率、负泊松比、各向异性导热、带隙调控以及拓扑边界态等一系列独特现象。自 21 世纪初电磁超材料中负参数模型和电磁隐身的概念被提出以来，该领域迅速扩展至声学、力学、热学等多物理领域逐渐形成了跨学科、跨尺度的研究热点[15-18]。

在电磁学领域，超材料最早被应用于探索负折射率和超透镜效应，其突破性成果迅速引起广泛关注[19-20]。随后，声学超材料的发展展示了对次波长声波传播的有效调控，使得低频噪声抑制、定向声传输和声学隐身成为可能。与此同时，机械超材料的兴起则更为广泛，涵盖从具有负泊松比的蜂窝与晶格结构到多稳态屈曲网络等多样化设计[21]。这类结构在能量吸收、振动隔离与冲击防护方面展现出优越性能。此外，近年来快速发展的超材料通过人工调控各向异性热导率与拓扑热流，实现了热隐身、热整流和温度场聚焦等前所未有的现象[22]。由此，超材料逐渐从最初的电磁领域扩展至声学、光学、热学、力学等多物理耦合方向[23-24]，形成了广泛而系统的研究格局。

推动这一领域快速演进的重要技术支撑在于制造手段的革新。增材制造(additive manufacturing, AM)的成熟极大地拓展了复杂三维晶格与层级结构的设计空间[25-27]，使许多曾经仅停留在理论层面的设计得以转化为真实物理样品。光固化(stereolithography, SLA)、双光子聚合(two-photon polymerization, TPP)、直写(direct ink writing, DIW)，以及粉末床熔融(powder bed fusion, PBF)等工艺的持续进步[28-32]，使研究人员能够在微米至厘米的尺度范围内制备多材料、多功能的超材料结构。与制造技术同步发展的，是人工智能与数据驱动建模在设计环节的兴起[33]。传统基于有限元与高保真数值仿真的设计路线往往耗费大量计算资源，而近年来涌现的拓扑优化、生成对抗网络(generative adversarial network, GAN)、变分自编码器(variational autoencoder, VAE)，以及物理信息神经网络(physics-informed neural network, PINN)等方法[34-38]，逐渐使得超材料的几何-性能映射从高代价的仿真过程转向快速近似和逆向设计。这种趋势使研究人员能够实现从需求出发，自动生成满足目标指标的结构，从而推动超材料走向真正意义上的“按需设计”与“可编程设计”。

然而，随着超材料研究不断深入，其在工程化落地过程中仍面临诸多挑战。首先，尺度分离与等效假设的有效性在很多实际应用场景下并不成立。例如，当单元尺寸与激励波长相当，或者在强非线性与屈曲响应主导的条件下，经典的均匀化与等效介质理论将显著偏离实际响应[39-41]。其次，制造过程中的偏差会对超材料性能产生极高的敏感性，尤其在带隙调控和局域共振类结构中[42]，微小的几何误差可能导致性能劣化甚至失效。此外，材料本身的疲劳、蠕变、老化与环境耦合效应，往往限制了超材料的使用寿命与稳定性[43-44]。再加上跨域表征缺乏统一的测试规范与指标体系，不同研究之间的对比性与可复现性受到影响。这些问题的存在表明，超材料距离大规模工程化应用仍有不小的差距，需要在理论、设计、制造、表征到应用的全链条上形成更为系统和规范化的研究模式。

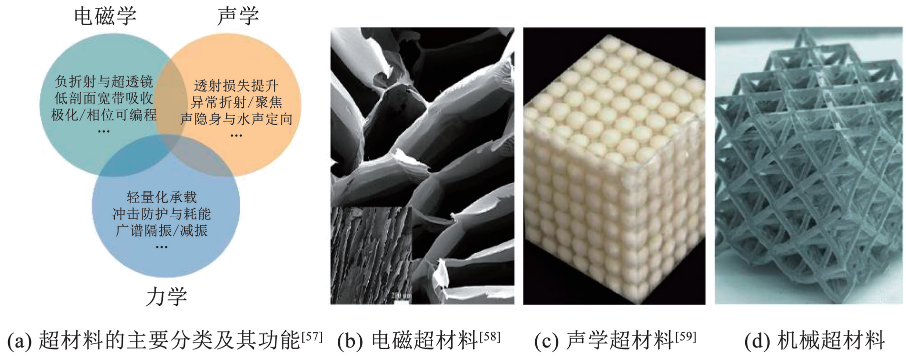
正因如此，近年来超材料研究逐渐从“奇异性能发现”的物理驱动阶段，转向“可编程单元构建”的工程导向阶段。越来越多的研究强调统一理论框

架的重要性,即从等效介质理论到色散关系,再到拓扑保护与非线性调控,形成连续而闭合的理论脉络[45-46]。与此同时,设计范式也在不断演进,从传统的参数化方法扩展到基于拓扑优化、贝叶斯优化、强化学习和生成式模型的多样化体系,并在设计过程中引入制造约束与容差鲁棒性,从而提升实际落地的可行性。制造层面,则强调跨尺度、多材料,以及 4D 打印策略,通过形状记忆、磁致动与电热响应等方式实现可重构与时变调控[47-49]。表征方法逐渐跨域化,力学、声学、电磁与热学的多场耦合测试正与数字孪生和物理约束反演结合,以期实现实验数据与数值模型的实时互馈。应用层面,超材料已在隔振与能量吸收、吸波与隐身、降噪与声聚焦、热管理、柔性电子与传感、生物医用与航空航天轻量化等方向[50]实现了从实验室验证到工程原型的逐步过渡。

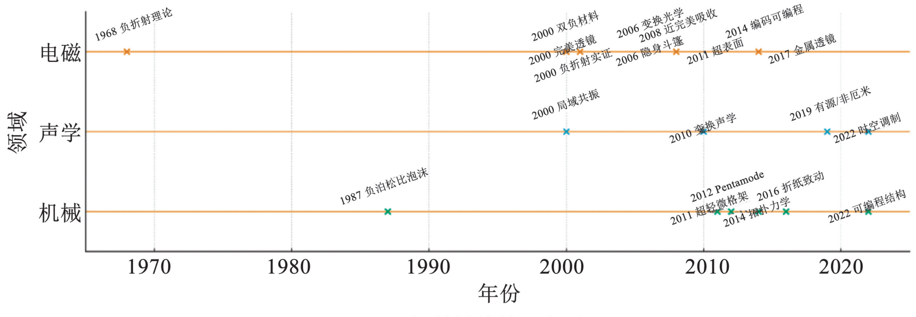
综上所述,超材料作为结构驱动功能化的典型代表,正在经历由基础科学探索向工程应用推广的转型期[51]。本文将围绕“理论、设计、制造、表征、应用、工程化” 6 条主线展开,系统梳理当前研究进展,比较不同方法学的优劣,讨论制造工艺的能力边界与挑战,总结跨域表征的指标体系,并构建典型应用的性能-结构-工艺矩阵。在此基础上,本文将进一步探讨前沿方向,包括可重构与时变拓扑、非厄米系统、多功能耦合与数字孪生闭环等热点议题[52-56],最后从可靠性、尺度放大、系统集成、标准化与合规、供应链与成本等方面提出工程化路径与未来展望。通过这一系统性综述,为超材料研究提供一个多学科交叉的综合视角,为该领域从实验室走向工程应用提供理论支撑与实践指导。

1　理论与建模基础

超材料作为一种基于结构设计而非材料本征性质实现功能调控的新型人工复合材料,其发展历程跨越了电磁学、声学与力学等多个领域。图 1 总结了超材料研究的主要分类及关键发展节点,展示了从电磁超材料到声学、机械超材料的演化脉络以及典型结构实例。可以看出,超材料的发展呈现出由单一物理场向多物理场耦合、由静态功能向可编程响应演进的趋势。这一演化的核心在于理论建模方法的不断完善——从早期的等效介质理论,到后来的布洛赫波色散分析,再到近年来引入的拓扑能带理论,为理解和预测复杂人工结构中的波传播行为提供了坚实的理论基础。



(a) 超材料的主要分类及其功能[57]　(b) 电磁超材料[58]　(c) 声学超材料[59]　(d) 机械超材料



(e) 超材料关键节点图[60-65]

图 1　超材料的分类和关键节点

Fig. 1　Classification and key milestones of metamaterials

1.1　等效介质与色散分析

超材料研究的最早突破源于等效介质理论的提出[66]。对于具有周期性或准周期性的微结构,当其几何特征尺度远小于作用波长或宏观结构尺寸时,复杂的微观几何可以被简化为等效的连续介质,进而以张量形式描述整体的力学、电磁或热学性质。这种均匀化方法不仅使得“负折射率”与“负泊松比”等概念得到清晰物理化表述,也为后续的理论建模和实验设计奠定了坚实基础。然而,均匀化模型并非在所有情况下都适用。当单元尺寸与波长接近,或者体系处于强非线性、几何屈曲或局域共振主导的工作状态时,等效模型往往会出现失效甚至给出完全错误的预测。

为克服均匀化方法的局限,布洛赫波与色散理论逐渐成为主流[67-68]。根据布洛赫定理,周期性结构中的场量可以分解为周期函数与平面波的乘积,从而使无限结构的问题得以转化为布里渊区的有限计算。通过求解色散关系,研究人员能够揭示波传播中的带隙特性、群速度分布和等向/各向异性行为。值得注意的是,等效介质理论与色散分析并非对立的研究范式,而是互为补充的描述方式。在长波极限下,等效模型可有效表征宏观响应;而当单元尺寸与波长相当或体系呈现局域共振、几何屈曲、强非线性等行为时,需借助基于等效介质或精细单元模型的布洛赫波与色散分析来揭示真实的波传播特征。这使得两大类带隙形成机制被系统阐明:1)基于单元内部共振的局域共振带隙;2)由周期性排列导致的布拉格散射带隙。随着拓扑学概念的引入,研究人员发现通过拓扑不变量可以预测界面或边界上的稳健传输态,这类拓扑边界态即使存在缺陷或制造误差时也能保持稳定。因此,从均匀化到色散,再到拓扑能带理论,超材料的建模体系逐渐由理想化向现实复杂场景演进,为设计可容错、可调控的结构提供了理论保障。

1.2　非线性与多稳态

除了线性理论揭示的色散与带隙行为,非线性与多稳态特性也逐渐成为超材料研究的重要组成部分[69-71]。许多超材料单元在受力时会表现出屈曲、剪切或折叠等几何非线性,这使其整体性能在不同构型之间发生突变。例如,在屈曲梁网络、折纸与剪纸结构以及准双稳态单元中,体系的能量势阱通常具有多个局部极小值,从而赋予结构可重构性与多模式响应[72-74]。这种特性使超材料能够在外部激励作用下切换工作状态,实现宽频减振、冲击吸收或自适应调控。非线性效应不仅能够带来显著的能量耗散,还能够诱导产生振幅相关的带隙、孤子传播,以及模态之间的强耦合现象。

由于传统的线性波动理论无法准确描述这些行为,研究人员发展出一系列新的建模方法。能量法能够通过势能地形揭示多稳态之间的转化路径;谐波平衡方法则适用于近周期振动响应的近似分析[75];显式时间积分在强非线性、冲击和大变形条件下尤为有效。这些工具的结合使得非线性超材料的建模逐渐从定性描述走向定量预测,为基于非线性效应的设计奠定了基础[76-77]。可以说,非线性与多稳态为超材料带来了一种“可编程”的物理内核,使其不再局限于被动的控制,而是能够主动实现构型切换与响应调节。

1.3　数据驱动与物理约束学习

随着超材料几何复杂度的不断提升,单纯依赖解析解或高保真有限元仿真的方法已无法满足高效设计的需求[78-81]。在庞大的几何参数空间中,传统优化往往面临维度灾难,计算代价极为高昂。数据驱动方法,特别是机器学习与人工智能的引入,为这一困境提供了新的解决方案。在众多方法中,PINN 表现优秀[82-83]。PINN 的核心思想是将控制方程、边界条件和守恒定律直接嵌入损失函数,使模型在学习有限数据的同时自动满足物理约束。这种方法显著降低了训练所需的数据量,并在小样本条件下展现出良好的泛化能力。

在数据驱动的框架下,研究人员逐渐将拓扑优化建模与深度学习方法相结合,用以在复杂设计空间中自动寻找最优结构拓扑。该类方法通常以连续体力学或多物理场耦合方程为基础,通过建立性能指标函数与约束条件,结合密度法(solid isotropic material with penalization,SIMP)、水平集法(level set method, LSM)或基于移动可变形组件/孔洞(moving morphable components/voids,MMC/MMV)等参数化

描述实现设计变量的迭代更新[84-87]。对于波动型超材料,可结合布洛赫边界条件与频域有限元分析,直接针对能带结构进行优化;而在多物理场耦合体系中,可进一步融合基于 PINN 的物理约束网络,实现高维高效的优化求解。这种“拓扑优化 + 物理学习”的融合策略不仅显著提升了设计效率与可制造性,也为实现可编程、可调控的智能超材料提供了系统化的建模途径。

研究人员还广泛采用降维方法,如主成分分析(principal component analysis, PCA)、自编码器(autoencoder, AE)等[88-90]。将高维几何与性能映射投影至潜空间,以便进行高效的优化与搜索。同时,不确定性量化(uncertainty quantification, UQ)也逐渐成为设计环节不可或缺的一部分,它能够评估制造误差、材料波动与环境扰动对性能的影响。通过将 UQ 与 PINN 结合,研究人员不仅能够获得预测模型,还能够在设计阶段就对结构进行鲁棒性评估,从而避免在制造环节暴露出严重缺陷。这一趋势表明,未来的建模与设计方法将逐步转向数据与物理的深度融合,既保持物理一致性,又具备高效的计算能力。

1.4 设计范式演进与“设计—验证闭环”

理论的进步直接推动了设计方法学的演进。早期的超材料设计多以参数化方法为主,通过调整孔径、壁厚或倾角等几何参数来实现目标性能。这种方法直观易行,但局限于较小的设计空间,难以挖掘复杂甚至反直觉的结构。拓扑优化的出现改变了这一局面。通过密度法、水平集法,以及变厚度壳/梁框架等方法,研究人员能够在大规模设计空间中自动搜索最优方案,从而在刚度、带隙宽度、能量吸收与质量等性能之间实现优化。多目标优化与帕累托前沿(Pareto front)进一步拓展了可能性,使得设计者能够在多个冲突指标之间进行理性权衡。

随着数据驱动方法的发展,生成式设计逐渐成为超材料领域的新方向。贝叶斯优化能够在样本有限的条件下高效找到全局最优解,而当存在大规模数据资源时,GAN、VAE,以及扩散模型等方法则能够在潜空间中生成符合物理约束的候选结构[91]。强化学习的引入更是为可重构与时变超材料的动态调控提供了可能,智能体通过试错学习和奖励机制能够掌握最优的加载与调节策略。

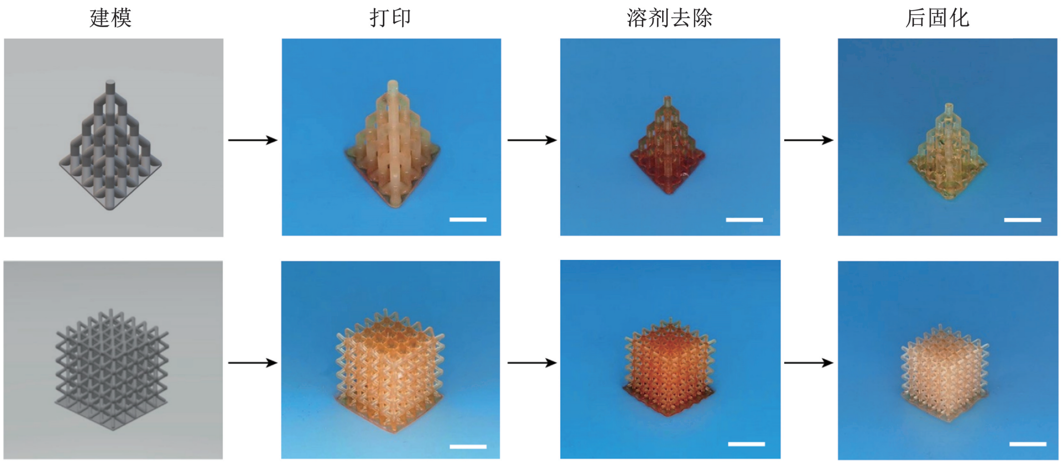
设计方法学的发展也推动了制造可行性与容差鲁棒性的显性化。研究人员逐渐意识到,如果设计的结构无法被现有工艺实现,或者对微小偏差过于敏感,那么再优越的性能也无法转化为现实。因此,越来越多的工作在设计阶段就引入打印分辨率、最小壁厚、构建方向与支撑可达性等约束[92-94],并通过形态学滤波与投影方法抑制数值优化中常见的棋盘格伪影。概率优化与对抗训练等方法则被用于增强结构在几何与材料波动下的稳健性。

在理论与设计深度融合的背景下,超材料研发正逐渐走向“设计—验证闭环”。这一闭环流程不仅包括从目标设定到优化、仿真与实验的全链条,还强调数字孪生的引入。通过实时将打印工艺参数与实测几何偏差反馈至仿真模型,数字孪生能够不断缩小理想设计与实际样品之间的差距[95]。最终,超材料的研发将不再是单向的“预测、验证”模式,而是动态迭代的循环,能够在设计、制造与表征之间形成互馈与协同。

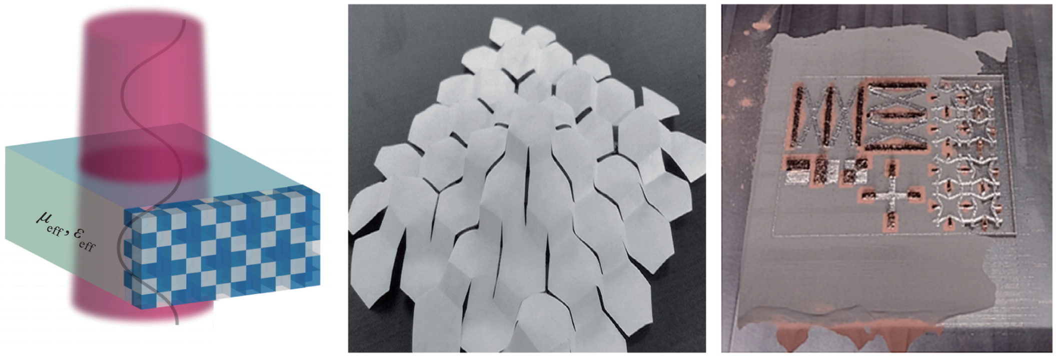
2 材料体系与制造

2.1 材料选择与性能权衡

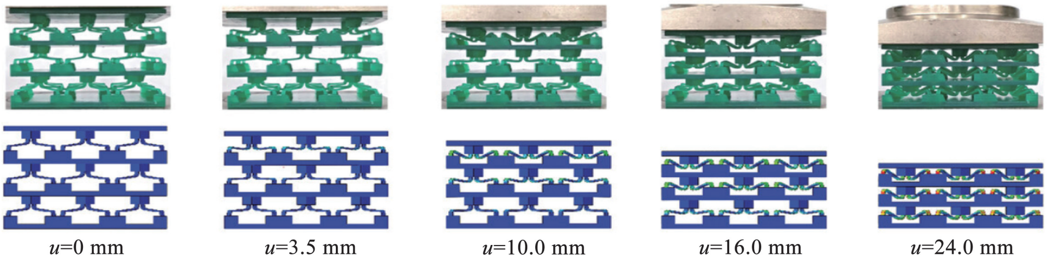
在超材料的构建中,材料本体的选择往往与几何设计同等重要。虽然超材料的性能主要由结构拓扑决定,但基体材料的力学、热学、电磁和环境适应性仍然深刻影响最终表现。常见的材料体系如图 2 所示,包括光敏树脂、热塑性与热固性聚合物、金属(如铝合金、钛合金和不锈钢)、折纸软材料、纤维增强复合材料以及等离子超材料和液态金属[96-98]。聚合物由于易加工、成本低和轻质的特性,被广泛用于实验室样品与功能原型的制备;金属和陶瓷因具有其高强度、高模量与耐高温等特性,更适合航空航天和极端环境下的应用。然而,强度、韧性、阻尼、导热、导电性与生物相容性之间的平衡常常构成难题。研究人员不得不在性能与制造可行性之间做出取舍,例如高强度金属晶格通常伴随高残余应力和制造缺陷,而柔性聚合物结构在能量吸收上表现出色,却在耐久性上受限。因此,实现材料属性与几何结构的协同设计,已成为推动超材料从实验室走向实际应用的关键环节。



(a) 树脂基超材料[99]



(b) 等离子超材料[100]　　(c) 折纸软材料[101]　　(d) 金属基超材料[102]



(e) 聚合物超材料[103]

图 2　不同基材材料的超材料

Fig. 2　Metamaterials based on different substrate materials

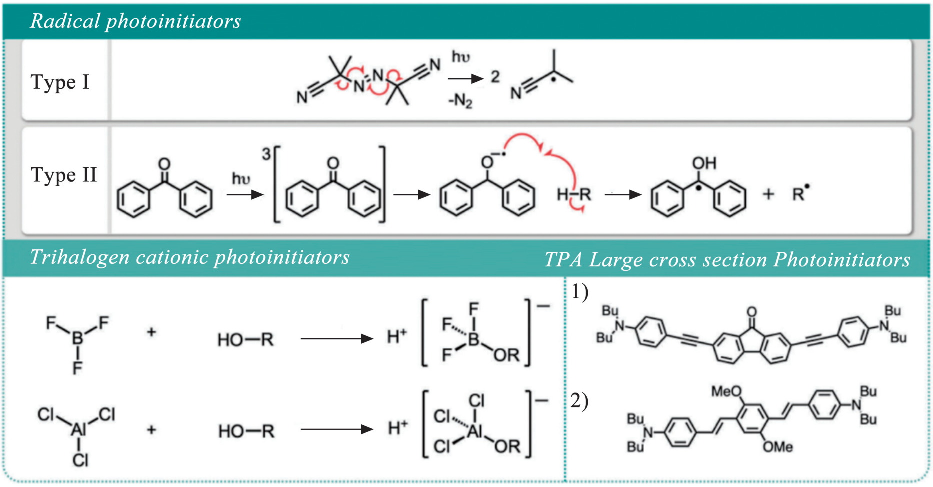
2.2　微纳尺度制造方法

在微纳米尺度,制造方法的突破是推动超材料发展的关键动力。双光子聚合(two-photon polymerization, TPP)因其 100 nm 的分辨率而成为制备微型光子晶体和超轻晶格结构的核心工艺[104-106]。该方法通过非线性光学效应在聚合物基体中实现局部固化,从而构建如图 3(c)所示的复杂三维微结构。虽然产率较低,但具有极限制造能力,为探索超材料的物理极限提供了实验平台。除此之外,聚焦离子束(focused ion beam,FIB)、电子束直写(electron beam lithography,EBL)等方法[107-108]同样可实现高分辨率加工,适用于金属与陶瓷超材料。然而,这些工艺普遍存在效率低、成本高的问题,难以实现规模化。为此,近年来出现了一些折中方法,如基于光刻与模板复制的批量制造工艺[109],使微纳尺度的光学与声学超材料逐渐具备一定的可扩展性。总体而言,微纳制造方法主要服务于基础科学探索,其价值在于揭示极端条件下的物理现象,而非直接面向工程应用。

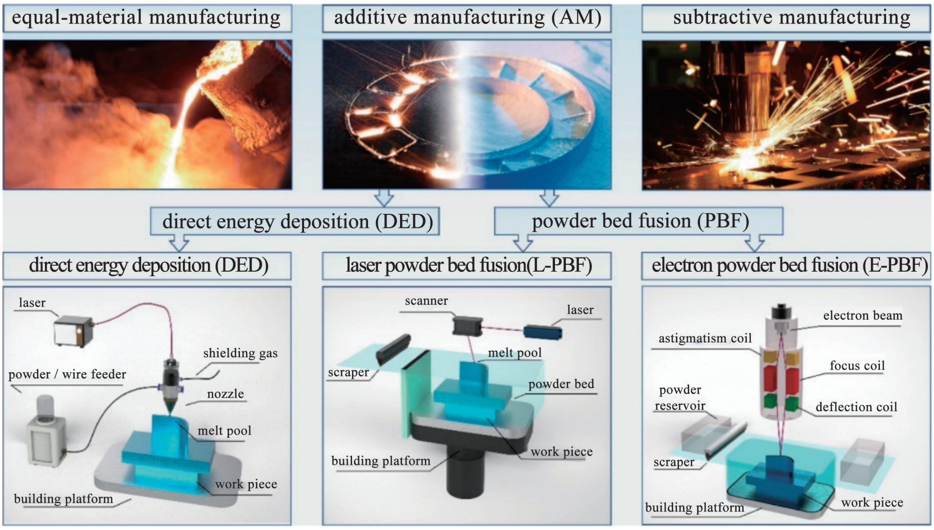
2.3　中尺度与宏观增材制造

随着增材制造(additive manufacturing, AM)的发展,超材料逐渐进入中尺度与宏观结构的制备阶段[110-112]。SLA 能够以较高精度构建厘米级复杂晶格结构,并在一定程度上支持多材料打印。DIW 则适合制备柔性结构与复合材料,尤其在 4D 打印领域展现潜力。金属增材制造方法(图 3(b)),包括 PBF、电子束熔化(electron beam melting,EBM)和定向能量沉积(directed energy deposition,DED),使得

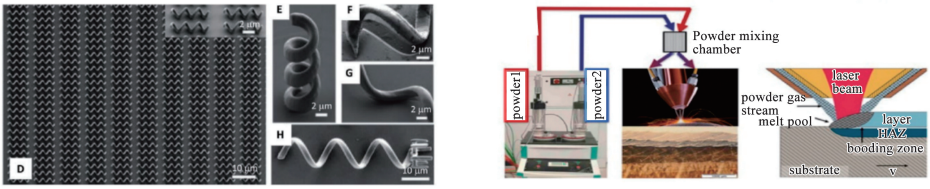
金属超材料成为可能[113-117]。这些工艺能够为航空航天和国防领域提供高强度轻量化部件,但同时带来各向异性、残余应力和表面缺陷等挑战。为此,研究人员常通过热等静压、热处理与表面精修等方式改善性能。相比之下,陶瓷与复合材料的增材制造仍处于探索阶段,但其潜力巨大,尤其是在高温防护和热屏蔽方面[118-120]。整体而言,中宏观增材制造的快速发展正在逐步消解超材料“可制造性”的瓶颈,为结构从实验室走向工程应用提供了现实路径。



(a) 光刻胶核心成分的活性物质[121]



(b) 不同的金属打印方法[122]



(c) 微纳尺度下的螺旋形微泳器　(d) 定向能量沉积打印[123]

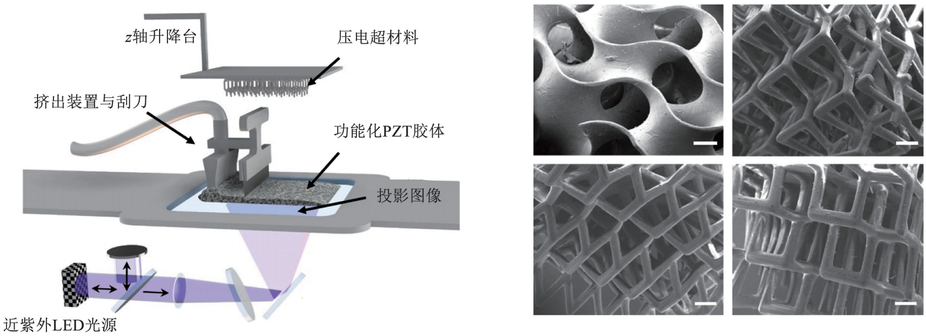
图 3　不同尺度的制造方法

Fig. 3　Fabrication methods accross different scales

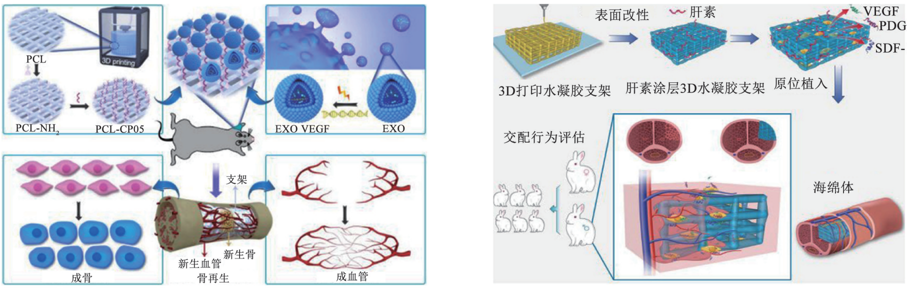
2.4　多材料与 4D 打印策略

在传统超材料中,结构一旦成型,其功能大多固定。然而,随着多材料打印与 4D 打印的出现[124-127],研究人员能够赋予超材料时变与可重构的能力。多材料打印通过在同一结构中引入不同性能的基元,使得单个超材料单元可以同时具备刚度梯度、阻尼分布或导电网络(图 4(a))[128-129]。4D 打印则进一步在结构中嵌入形状记忆聚合物、磁致伸缩材料或液态金属通道,使得超材料能够在外场刺激下实现构型切换、带隙漂移或功能激活。例如,通过电热激励改变局部曲率的晶格结构,可以在不同工况间实现动态调控(图 4(f));通过磁场调控嵌入的软磁单

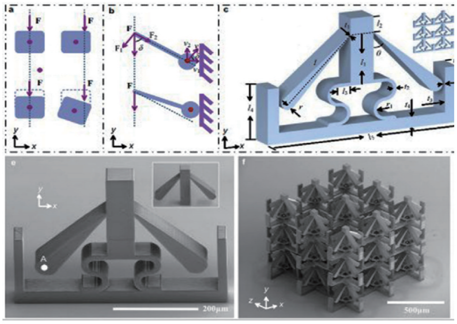
元，则可以实现带隙的实时调控。这类策略拓展了超材料从静态功能走向动态可编程的边界，为智能防护、可穿戴设备和软体机器人等新兴应用奠定了基础[130－132]。



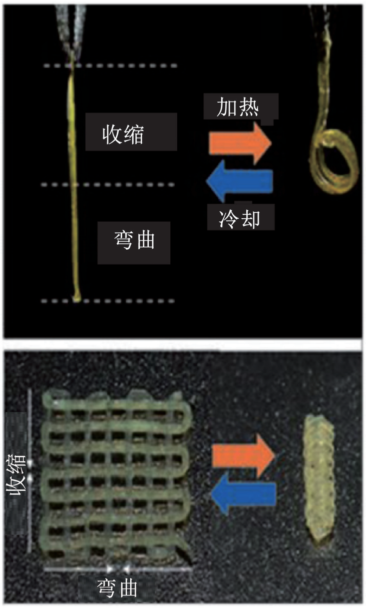
(a) 3D打印压电材料[133]

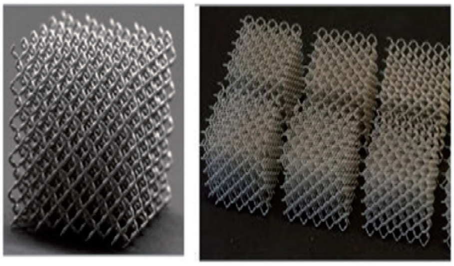


(b) 3D打印多孔支架促进骨骼形成与血管生成[134]　(c) 利用3D打印水凝胶支架重建受损阴茎海绵体[135]



(d) 具有不同变形特性和应变率依赖性力学响应的材料[136]





(e) 可调渗透性的钛合金生物相容性五模超材料[137]

(f) 热敏型LCE结构通过温度变化引发弯曲/卷曲的可逆形变现象[138]

图 4　多材料与 4D 打印

Fig. 4　Multimaterial and 4D printing

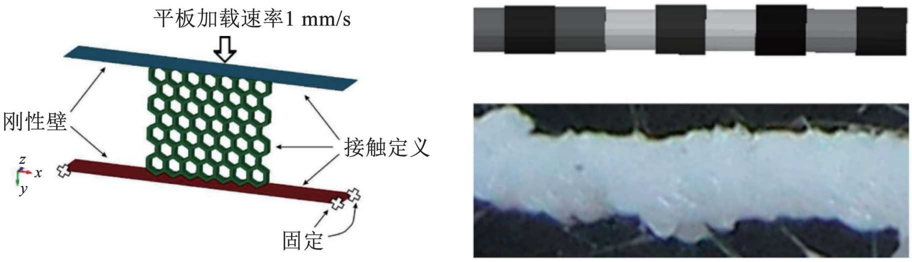
2.5　可扩展制造与可持续性

尽管实验室层面的创新制造方法层出不穷，但要实现超材料的大规模应用，仍需考虑可扩展性与可持续性[139－141]。高效制造不仅关乎生产效率和良品率，还涉及全生命周期的成本控制与环境影响。在规模化方向，模块化单元拼接与高速并行打印被认为是潜在方案，它们能够在保证复杂性的同时提高生产效率。在可持续性方面，材料循环利用与可拆解连接逐渐受到关注。例如，通过可降解聚合物或可逆黏结剂实现超材料的回收与再制造，不仅有助于降低成本，也有助于减少碳足迹[142]。随着制造与环境问题逐渐被纳入考量，未来的超材料设计将不仅局限于性能指标，还需要综合考虑制造效率、经济性与环境友好性，从而实现工程化的全面落地。

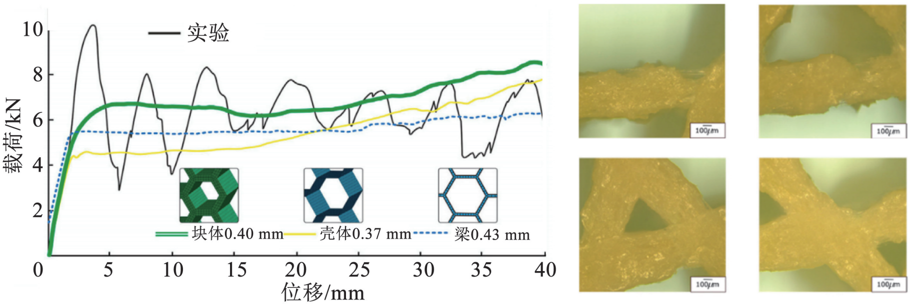
3 表征与验证

3.1 力学性能的多尺度表征

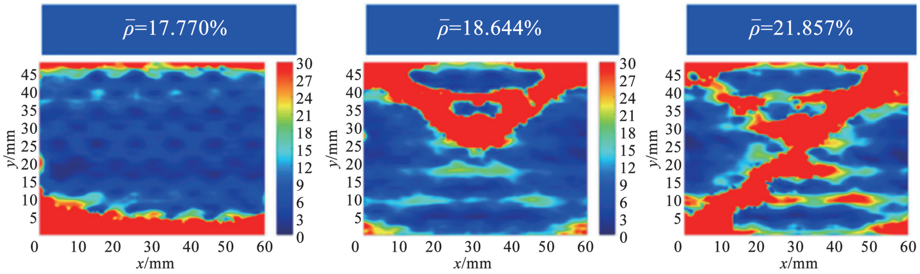
力学表征是结构型超材料研究的核心，需在“几何-胞元-结构”多尺度上统一指标与机理(图5)。在准静态条件下，常用等效模量、泊松比、屈曲序列与比能量吸收(specific energy absorption, SEA)等指标评价承载与耗能，并结合实体/壳/梁等不同有限元与实验对比澄清厚度效应与局部屈曲(图5(a)、5(c))。对非均匀截面或梯度构型的梁/支撑元件，引入顺应度与临界屈曲等构型敏感指标以刻画刚度与失稳路径(图5(b))。场测方面，数字图像相关(digital image correlation, DIC)可获得全场应变与局域化带，从而在不同相对密度的胞格间建立“密度-局域化-等效性能”的映射(图5(e))。显微观测揭示底面缺陷、分层与层间裂纹对应力平台与峰值承载的影响(图5(d)、5(g))。在动态与冲击工况下，色散/带隙与几何非线性诱导的耗能抑制应力波传播，宜采用冲击响应谱(shock response spectrum, SRS)、传递率与截止频率等指标，并结合频散与局域共振进行归因；拓扑超材料中位错诱导的零模与自应力表征其“拓扑-局域-耗能”的选择性(图5(f))。疲劳与寿命评估可通过S-N曲线、循环稳定性与断口形貌三位一体完成，并将缺陷统计与制造公差显式纳入模型，实现从微观质量到宏观可靠性的闭环标定。



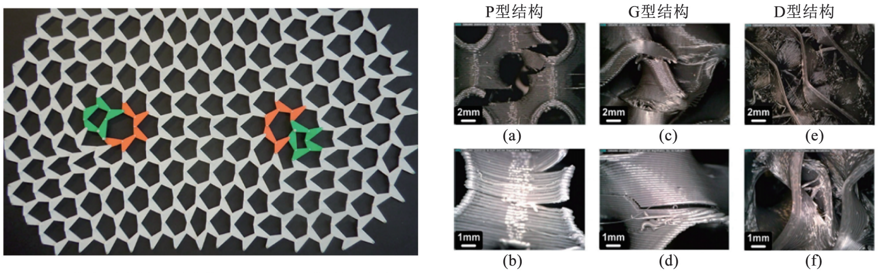
(a) 六边形蜂窝压缩测试模型[143]　(b) 非均匀截面支撑梁模型[144]



(c)不同有限元类型(砖块、壳体和梁)对ABS六边形蜂窝的载荷-位移曲线进行实验与有限元模拟对比　(d) 显微图像显示PLA-木格栅样品底面存在缺陷[145]



(e) 通过DIC分析获得的准静态加载条件下不同相对密度的细胞材料(开尔文单元)变形分布[146]



(f) 拓扑超材料左侧位错处局域化的零模，对应右侧位错处的自应力状态[147]　(g) 不同TPMS结构在15%应变下的断裂区域，显示分层和层间裂纹扩展[148]

图5　超材料的力学性能表征

Fig. 5　Mechanical characterization of metamaterials

随着弹性波超材料在波控、隔振及拓扑能带调控等领域的快速发展,实验表征手段的精度与可视化能力对揭示其波传播机理至关重要。激光多普勒测振技术(laser Doppler vibrometry, LDV)凭借其非接触、高灵敏度和高空间分辨率等优势,已成为研究弹性波超材料中波场特性的重要实验工具。其基本原理是通过检测振动表面对入射激光的多普勒频移来获取局部振动速度信息,从而实现结构表面振动响应的精确测量。

3.2　声学、电磁与热学性能的跨域验证

超材料研究的重要特征是跨物理场的多功能耦合,因此表征方法也必须突破单一学科的局限。声学超材料的性能通常通过测量吸声系数、透射率和散射参数来表征。低频吸声与带隙形成的效果尤其受到关注,因为这直接决定了在噪声控制和声聚焦应用中的有效性。电磁超材料与超表面的表征通常采用矢量网络分析仪(vector network analyzer, VNA)测量散射参数 S,以获取其透射与反射特性。在实际应用中,入射角与偏振的独立性也常被用作评价指标,因为这关系到隐身与吸波装置的适用范围。热学超材料的表征相对复杂,其性能涉及稳态与瞬态导热行为。研究人员通常通过红外热像监测温度场演化,进而反演等效导热张量、热整流比与散射强度。随着热学超材料逐渐进入应用验证阶段,如何建立标准化的热流控制测试平台已成为关键问题。跨域的多场表征不仅有助于揭示各类超材料的独特性能,还为探索其耦合效应提供了实验支撑。

3.3　多场耦合与原位测试方法

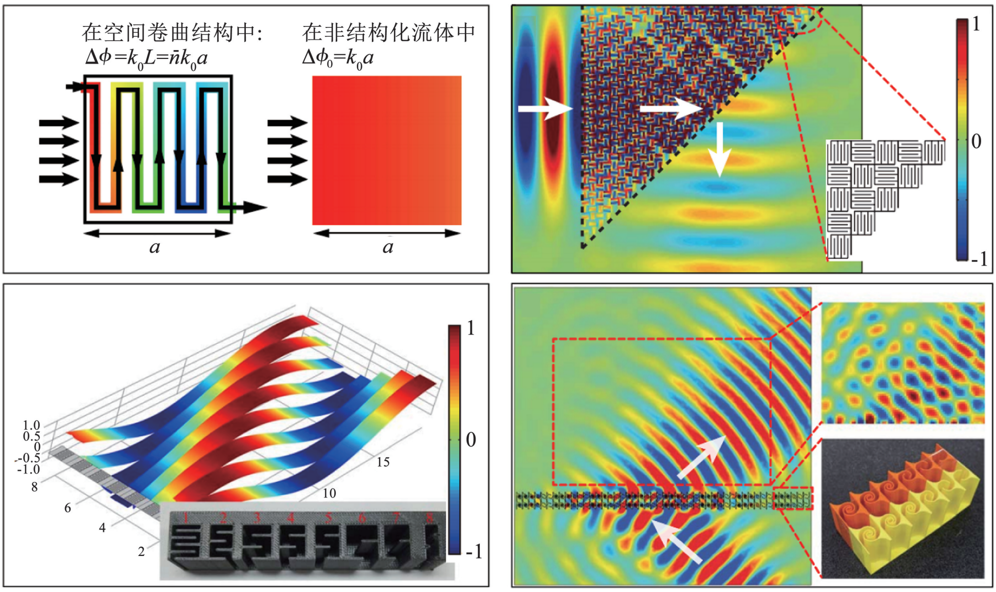
随着应用场景对多功能耦合提出更高要求,单一条件下的性能测试已难以满足研究需求。多场耦合表征逐渐成为趋势。例如,在机电耦合超材料中,力学加载与电信号输出必须同步采集;在热机耦合体系中,温升与力学响应需要实时监测。数字图像相关(DIC)技术能够在加载过程中捕捉全场应变分布,与同步红外热像、电学传感和声学阵列结合,可以实现对耦合响应的全面解析。近年来,原位测试技术快速发展,使研究人员能够在显微镜或同步辐射光源下直接观察微结构的演化过程。这种方法不仅揭示了局域屈曲、裂纹扩展等微观机制,也为建立从微结构到宏观性能的多尺度模型提供了关键证据。此外,结合物理约束反演与 PINN 的数据驱动方法逐渐兴起,它们能够在实验采集的有限数据基础上,推断出隐含的材料参数与边界条件,从而缩小实验与仿真之间的差距。

3.4　标准化、复现性与开放数据

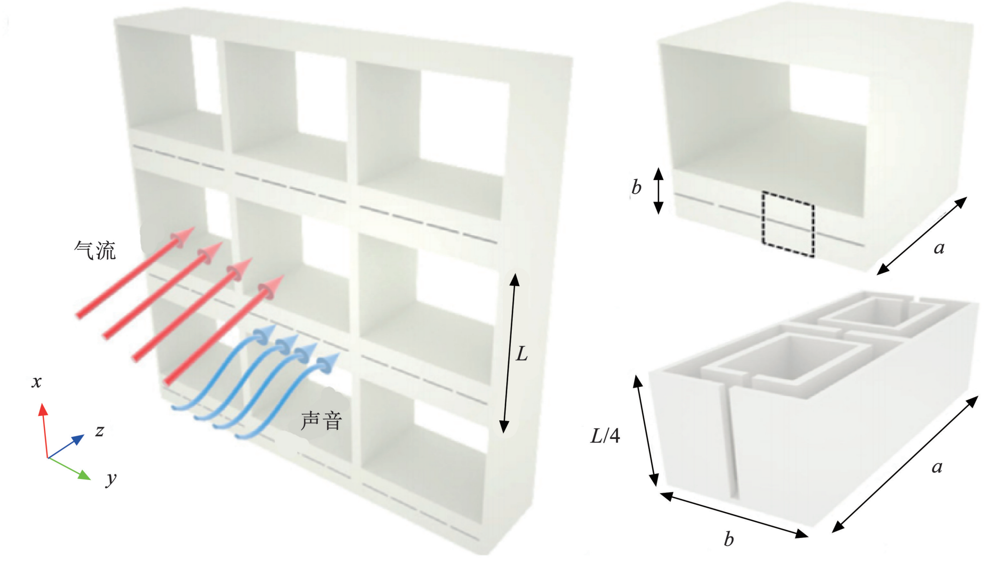
尽管超材料的研究成果层出不穷,但在表征方法上仍存在显著的标准缺失问题。不同研究团队在样品尺寸、加载方式、边界条件与评价指标上的差异,使得结果之间难以直接比较。例如,在机械超材料中,SEA 的定义与归一化方式常常不一致,导致同类研究的数据无法互证;在电磁与声学领域,吸收带宽、相对带宽与带隙定义的差异同样阻碍了横向对比。为提升研究的可比性与复现性,近年来逐渐出现一些倡议与实践,包括建立统一的样品制备规范、标准加载谱以及统计分析方法。此外,开放数据平台的建设被认为是推动该领域健康发展的重要举措。通过公开 CAD 模型、仿真网格、实验数据与可视化方案,不仅能够增强结果的透明度,也为后续研究人员提供了宝贵的基准库。未来,随着超材料逐渐进入工程化阶段,类似航空航天与生物医学领域的标准化体系有望被引入,从而实现从基础研究到产业应用的顺畅过渡 。

3.5　声学操控与噪声治理

声学超材料的发展拓展了人类对声波传播调控的能力。传统吸声材料往往在中、高频段表现良好,而在低频段效率极低。通过引入亥姆霍兹共振器、膜片与板振子,研究人员成功实现了深亚波长条件下的低频吸声。此外,基于声学超表面的设计能够实现对声波相位、幅度与传播方向的精准调控,从而完成异常折射、波前整形与声聚焦(图 6(a))[149-151]。在通风与吸声的权衡问题上,近年来出现了一系列创新设计,例如在多孔材料中嵌入膜片结构,实现同时具备良好透气性与高效降噪性能的双功能单元。这些成果在建筑声学、环境噪声控制(图 6(b))和水下声学等领域具有广阔应用前景。值得注意的是,声学超材料不仅用于噪声治理,还逐渐应用于超声成像与医学治疗,例如通过超表面实现声能聚焦,提高超声消融与成像分辨率[152]。



(a) 空间卷绕结构及其内部声压场[153]



(b) 超开放通风超材料吸收器机器内部单胞结构[154]

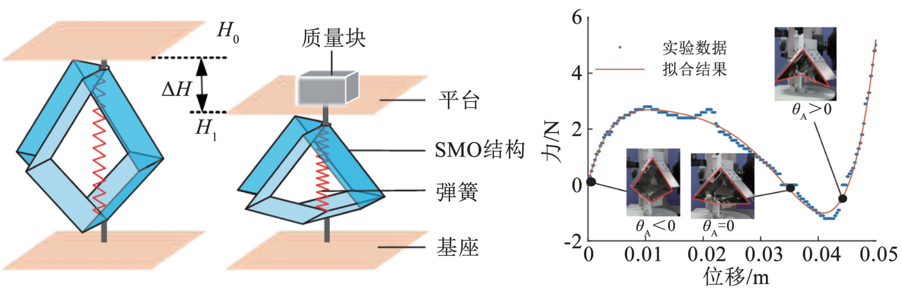
图6 声学超材料的设计与应用

Fig. 6 Design and application of acoustic metamaterials

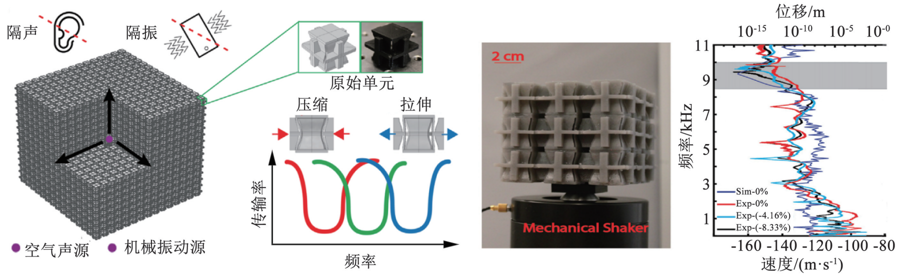
4 超材料的主要应用方向

4.1 隔振与能量吸收

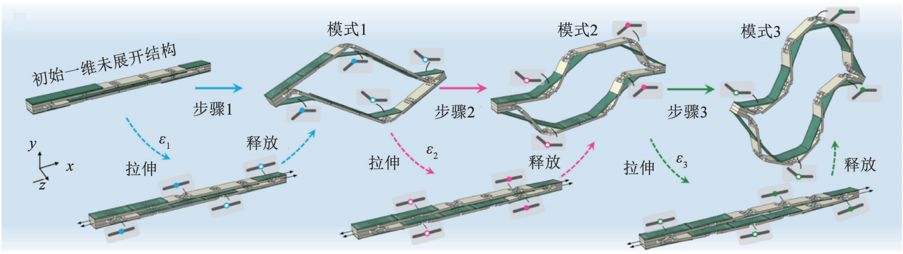
隔振与能量吸收是机械超材料最早且应用最广的方向之一。传统减振/防护多依赖高阻尼材料或复杂隔振器,而超材料可借助几何构型在宽频带内实现振动抑制与冲击吸收[155-156]。局域共振型结构可在远低于布拉格极限的频率开辟带隙,阻断低频波传播;折纸、屈曲梁与多稳态网络在外载下呈现强非线性与滞回耗能,显著提升比能量吸收。工程实现中,层级化与梯度化设计用于推迟失稳、分散冲击并提高损伤容限;例如,负泊松比蜂窝与弯曲梁网络已在防护垫层中完成原型验证,而集成磁流变阻尼层的多稳态晶格展现环境适应与可调控性[157-158]。近期,堆叠三浦折纸隔振器(stacked miura-ori, SMO)通过可编程折展实现可调刚度与宽频隔振(图7(a)、7(b));压缩振动声学超材料可在外压作用下同步衰减弹性波与声波,实验/数值频响函数在不同变形状态下吻合良好(图7(c)、7(d));基于双稳态铰链的多步骤多模态晶格实现序贯能量俘获与梯度阻抗匹配,支撑多场景吸能变换应用(图7(e)、7(f))。随着相关机理与制造工艺成熟,此类超材料正由实验室样品加速迈向工程级应用。



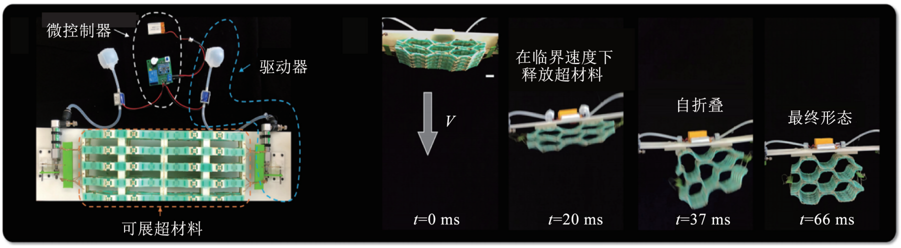
(a) 堆叠三浦折纸隔振器(SMO)原理图[159]　(b) SMO结构力-位移曲线



(c) 压缩振动声学超材料能够通过对外部超材料施加外力同时衰减弹性波和声波[160]　(d)0%、4.16%和8.33%变形状态下样品的实验频率响应函数与数值频率响应函数对比图



(e) 双稳态铰链实现的多步骤多模态机械超材料[161]



(f) 多步骤变换超材料的应用

图 7　隔振和吸能超材料

Fig. 7　Vibration-isolating and energy-absorbing metamaterials

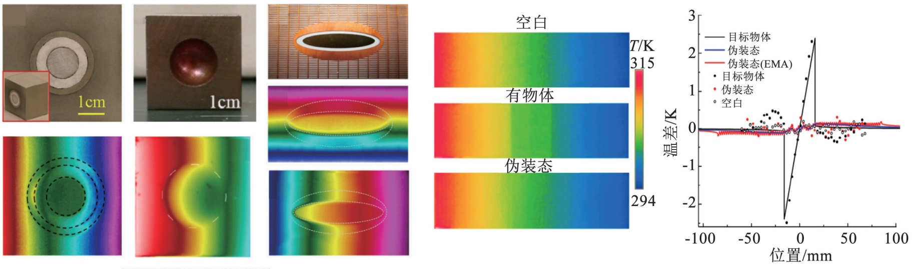
4.2　电磁吸收与超表面应用

电磁超材料自诞生即与负折射与隐身紧密相关，但近年重心转向宽带吸收、极化调控与低剖面超表面。通过多谐振单元的级联与耦合，可在宽频段内实现稳定高吸收以满足隐身与电磁兼容需求[162-163]。编码/可编程超表面推进了波前调控的数字化，使相位、幅度与极化可独立控制；柔性与曲面实现进一步扩展了对复杂平台的贴合与覆盖。除吸波与隐身外，相关技术在天线、无线能量传输与信息调制等方向展现潜力。与热辐射耦合时，纳米光子与二维材料平台实现“电-热-光”协同调控。例如通过电调制石墨烯谐振器阵列或含 GaAs/n-AlGaAs 量子阱的光子晶体板改变载流子密度，可获得可调（窄带）热辐射，支持辐射选择与实时整形（图 8（c）、8（d））。面向辐射冷却等应用，纳米光子结构实现对太阳光与大气窗的光谱选择，为超表面吸收/发射的系统级协同提供路径（图 8（e））。

4.3　热管理与热隐身

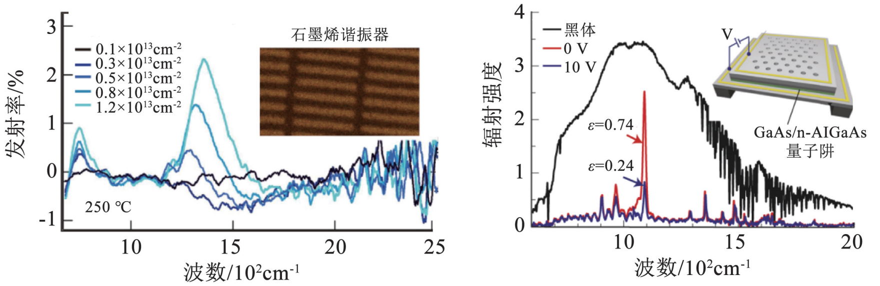
热学超材料通过调控等效导热张量与热流路径，为散热与热防护提供新范式。基于变换热学的热隐身/热透镜可使热流绕避或聚焦；热整流与热二极管实现热流单向传输，在电子散热与能量回收中

极具价值[164－165]。相变材料嵌入与层级拓扑设计使稳态/瞬态温度场可编程控制，正在向航天热防护与高功率器件散热延伸。双层热防护罩展示了结构－辐射协同下的温度场管理，并可通过测量热分布曲线对表面温度偏差进行定量比较(图8 (b))。需要强调的是，与声学/电磁相比，热学实验更具挑战，建立统一的测试方法、边界条件与评价体系仍是工程化瓶颈[166]。



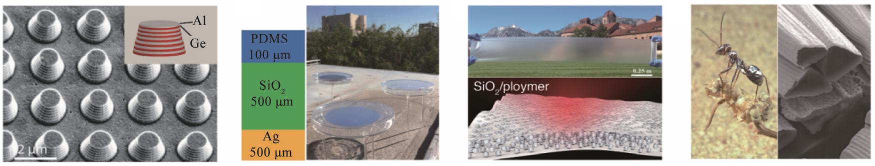
(a) 双层热防护罩演示

(b) 辐射热防护置时的测量热分布曲线
表面温度偏差的定量比较[167]



(c) 通过电调制石墨烯谐振器阵列中的载流子密度实现可调热辐射

(d) 通过电调制含有GaAs/n-A1GaAs量子阱的光子晶体板中的载流子密度实现可调窄带热辐射[168]



(e) 用于日间辐射冷却的纳米光子结构[169]

图8　热管理和辐射控制超材料

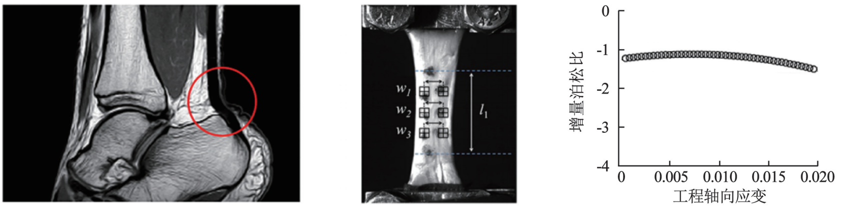
Fig. 8　Metamaterials for thermal management and radiative control

4.4　可穿戴应用

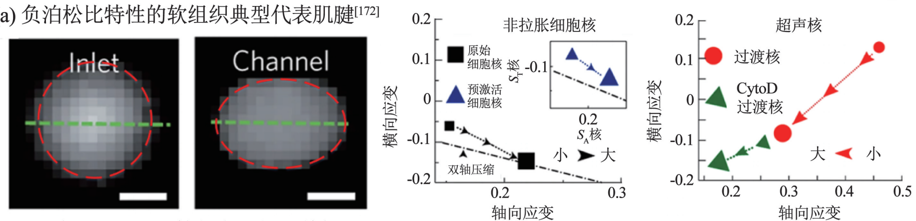
随着柔性电子与可穿戴设备的发展，机电耦合超材料逐渐成为研究热点。通过在结构单元中嵌入摩擦电纳发电机(triboelectric nanogenerator，TENG)或压电材料，研究人员能够将外部力学激励直接转化为电信号，实现自供能传感与人机交互。例如，基于多稳态晶格与 TENG 的鞋底结构能够在步态过程中实时采集信号，并通过深度学习模型反演运动模式。这种力－电映射的建立使得超材料在健康监测、运动分析和智能防护中展现应用潜力[170－171]。此外，柔性互连与封装策略的发展提高了此类超材料在复杂环境下的耐久性与稳定性，使其能够在汗液、湿气与温度变化中保持性能。这一方向的研究体现了超材料从宏观防护向微观感知的跨越，也为未来智能穿戴与人机接口提供了新的材料平台。

4.5　生物医用

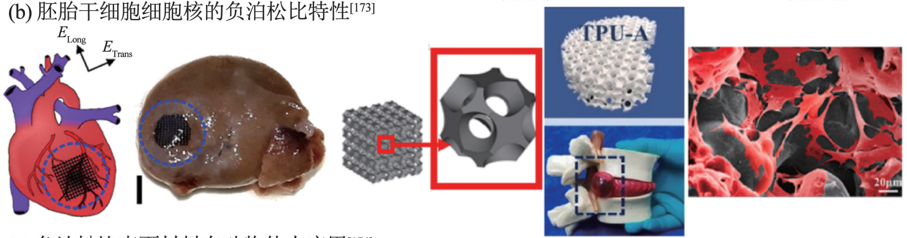
在生物医用领域，超材料的可设计性使其能够在力学支撑与生物相容性之间取得平衡。部分软组织与细胞体系天然呈现负泊松比特征，为仿生设计提供了力学参照(图9(a)、9(b))。面向植入与组织再生，基于拓扑优化与多材料打印可构建孔隙率梯度支架，在满足刚度与承载的同时促进细胞浸润与骨再生；负泊松比(negative poisson's ratio， NPR)表面材料已展现体内应用可行性(图9(c))。进一步地，二维混合超生物材料通过单元几何与材料组分协同调控细胞黏附、展铺与骨架重构，其 SEM/荧光成像揭示了 PPR/NPR 区对成纤维细胞与 hMSCs 的差异响应以及 F－肌动蛋白的重排(图9(d)～9(f))；细胞与2.5 *D* 圆柱形超生物材料的相互作用验证了曲率与各向异性对细胞形态与力学微环境的调制(图9(g))。同时，柔顺机器人与可调刚度器械为微创手术与术后康复提供了可集成的平台。



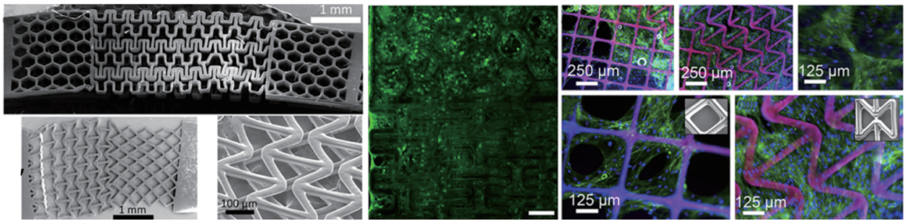
(a) 负泊松比特性的软组织典型代表肌腱[172]



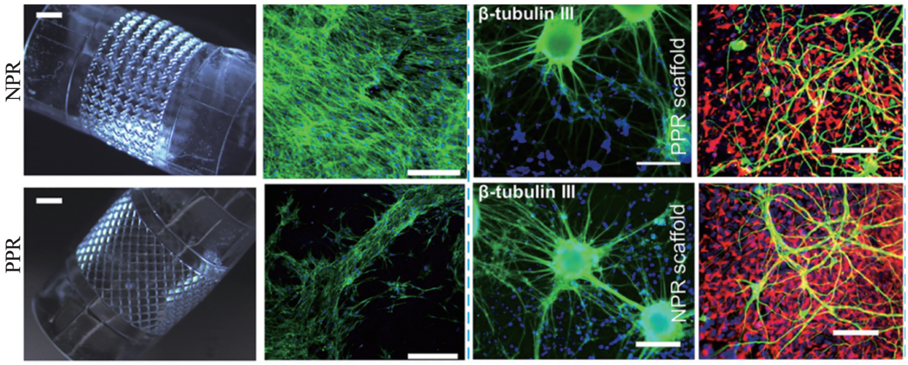
(b) 胚胎干细胞细胞核的负泊松比特性[173]



(c) 负泊松比表面材料在动物体内应用[174]



(d) 两种不同二维混合超生物材料及其SEM图像示例[175]　(e)PPR区与NPR区的荧光图像[176]　(f) 混合超生物材料中F-肌动蛋白与细胞核的荧光图像



(g) hTMSCs与2.5*D*圆柱形超生物材料的相互作用[177]

图 9　生物医用超材料

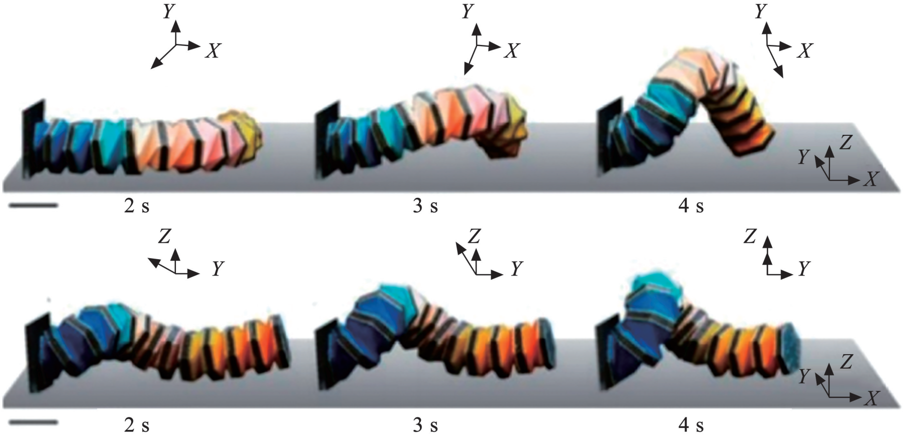
Fig. 9　Biomedical metamaterials

4.6　软体与集群机器人

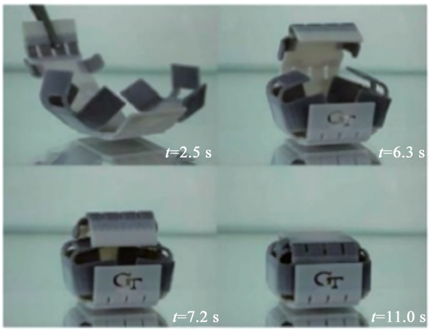
在传统超材料中,结构一旦制备完成,其功能通常是固定的。然而,随着可重构与时变超材料的兴起,研究人员逐渐打破了这一限制。通过几何驱动与外场激励,超材料能够在不同工作模式之间切换,实现实时调控与动态响应。几何驱动方式包括折纸、剪纸与软体变形单元(图 10(a)~10(c)),它们通过可逆的构型转换实现带隙漂移或传播路径切换。外场激励则涵盖电场、磁场、热场与气动压力(图 10(d)),例如通过电热致动控制形状记忆聚合物的曲率,或者利用磁场操控嵌入的软磁单元,使结构在不同频段展现不同的传输特性。这种时变性不仅使超材料具备可编程属性,还拓展了其在波束扫描、自适应隐身和智能传感中的应用空间。近年来,研究人员还提出了时空调制超材料的概念,通过在时间维度引入周期性扰动,能够打破传统的能带对称性,实现非平衡拓扑态与单向传输。这一方向的发展预示着超材料将从静态功能单元迈向智能材料系统。

随着柔性电子与软体机器人技术的快速发展,

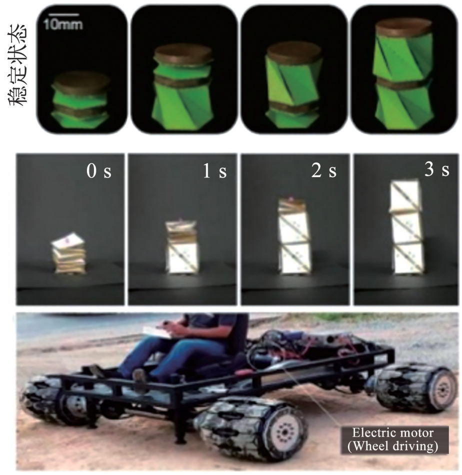
超材料逐渐与智能驱动和群体机器人融合。液态金属、导电弹性体,以及多通道网络的引入赋予结构高度可变形性与电/热可调特性,使其在拉伸、弯曲或压缩条件下依旧保持功能稳定,适用于可穿戴器件、柔性电路与生物医用植入物。折纸启发的结构为软体机器人提供了独特的运动模式:如基于章鱼臂的折纸机器人实现可编程扭转动作(图 10(a)),而3D/4D打印折叠结构在受热激活后表现出自锁与可重构功能(图 10(b))。基于 Kresling 折纸的磁致动单元更是推动了软体驱动与可变形车轮的结合(图 10(c))。此外,光/热刺激触发的软体机器人展示了多物理驱动下的可控变形与运动(图 10(d))。与此同时,集群机器人超材料的概念逐渐浮现。通过设计大量分布式单元,使其具备局域通信与协作能力,群体在宏观尺度上展现整体功能,如自愈合、形状编程与群体运动。这一思路将“结构即功能”扩展至“个体即系统”,为自适应工程与分布式智能开辟了新平台。软体与集群机器人超材料的探索不仅彰显了材料科学与智能控制的深度融合,也为未来的仿生工程与自适应系统提供了全新路径。



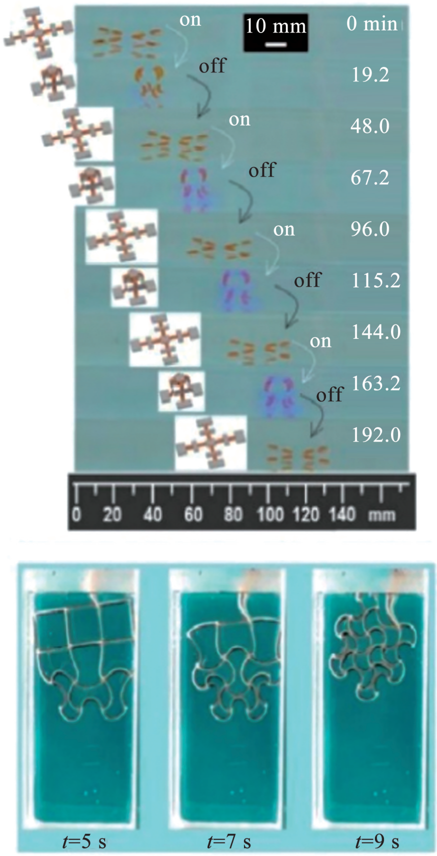
(a) 折纸章鱼臂状机器人的扭转动作[178]



(b) 加热状态下带有自锁装置的折叠盒[179]



(c) 基于Kresling折纸设计的磁致动组件及其在可变形车轮上的应用[180-181]



(d) 光刺激和热刺激触发的软体机器人[182-185]

图 10　可变形超材料及其应用

Fig. 10　Deformable metamaterials and their applications

5　工程化挑战

超材料要从实验室走向工程应用,首先面临的挑战就是可靠性问题。与传统材料相比,超材料依赖于复杂的几何构型,其性能高度依赖微观结构的完整性。这使得其在长期服役中极易受到制造误差、材料疲劳、蠕变与环境老化的影响 。例如,层级晶格在循环加载下往往会发生局部屈曲与裂纹扩展,从而引起宏观力学性能的衰减。在高温、高湿或辐照环境中,聚合物基超材料容易出现性能退化,而金属超材料则可能在热循环下发生微裂纹积累[186-187]。因此,建立针对超材料的加速寿命模型与多尺度失效树显得尤为重要。近年来,研究人员逐渐引入结构健康监测(structural health monitoring,SHM)手段[188],通过嵌入式传感与在线监测来实现服役过程的状态评估。未来,可靠性研究不仅需要关注单一性能指标,还必须考虑环境适应性,使超材料能够在复杂工况下长期保持稳定。

另一个制约超材料工程化的瓶颈在于尺度放大与系统集成。许多在实验室中验证有效的单元或小规模阵列,往往难以直接扩展到实际装备中[189-190]。一方面,制造误差在大尺寸样品中会累积放大,导致性能显著下降;另一方面,超材料需要与传统部件通过界面或连接件集成,而界面处的应力集中和热循环往往成为薄弱环节。为解决这一问题,模块化设计与标准化接口逐渐成为趋势。通过将超材料分解为可重复的标准单元,再通过拼接与组装实现整体功能,可以有效降低放大过程中的不确定性。此外,混合结构也是一种可行路径。例如,将蜂窝或夹层材料与超材料组合,可以在保证性能的同时降低制造成本与复杂度[191]。系统集成不仅涉及结构与性能的兼容性,还涉及传感、驱动与控制系统的协同[192-194]。未来,超材料需要在“材料—结构—系统”的多层次集成框架下发展,才能真正进入工程装备。

值得注意的是,近年来已有多种超材料实现了从实验验证到原型系统的转化,为工程化提供了可行路径。例如,基于局域共振原理的机械超材料减振垫已成功应用于精密设备与轨道交通隔振系统[195];声学超材料隔声板在建筑声学与航空舱段中展现出优异的低频噪声抑制能力[196];热超材料在电子封装与热隐身装置中实现了各向异性导热调控[197];拓扑超材料梁与板结构被用于航空航天领域的轻质抗振组件[198];同时,可编程与 4D 打印超材料在柔性机器人与智能防护装备中展现自适应变形与能量吸收功能[199]。这些实例表明,超材料正逐步从概念验证走向多场景工程化,展示出在隔振降噪、热管理与结构功能一体化方面的广阔前景。

6　结论

1)本文系统回顾了超材料从其优异性能发现到可编程设计的演化路径,构建了由“理论-设计-制造-表征-应用-工程化”贯通的研究主线。通过梳理等效介质、布洛赫波与拓扑能带等建模理论,揭示了多物理场耦合超材料的波动机理与界面特性;并指出非线性与多稳态效应的引入使得超材料具备动态响应与可重构潜能,为智能化与可编程超材料的研究奠定了理论基础。

2)在方法层面,超材料设计已由几何参数调控迈向基于拓扑优化、生成式模型与强化学习的智能优化体系,形成“目标设定-优化生成-仿真验证-实验反演-再设计”的闭环流程。制造技术方面,增材制造与 4D 打印的兴起极大拓展了可实现的结构维度与功能集成度,使多材料、时变结构与可重构晶格成为现实。表征手段的跨域融合促进了力学、声学、电学、热学多场性能的统一评估,并借助原位监测与数字孪生实现了实验-仿真的动态互馈。研究结果表明,超材料在隔振与能量吸收、低频降噪、电磁隐身、热调控、柔性电子、生物医用,以及航天轻量化等方向已实现从原理验证到原型应用的突破。

3)超材料的大规模应用仍面临可靠性、尺度放大、成本与标准化等挑战。未来研究应重点建立跨尺度、多物理场统一建模框架,实现理论与实验的动态校准;在设计层面强化稳健性与容差优化,确保结构在制造偏差与环境扰动下仍具稳定性能;在工程层面推进多目标优化,实现性能、成本与可靠性之间的平衡。可重构与时变超材料、智能材料与人工智能算法的深度融合,将推动超材料在通信、传感、能量传输与自适应防护等领域实现实际应用。总体而言,随着先进制造、数字孪生与数据驱动设计的协同发展,超材料将从“结构即功能”的科学概念,成长为未来 10~20 年内支撑高端工程与产业创新的核心材料平台。

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