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Architected Cellular Materials

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Keynote Topic

This article is part of the **Materials Issues in Additive Manufacturing** keynote topic compilation.

Annu. Rev. Mater. Res. 2016. 46:187–210

First published online as a Review in Advance on April 21, 2016

The *Annual Review of Materials Research* is online at matsci.annualreviews.org

This article's doi:
10.1146/annurev-matsci-070115-031624

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Keywords

lattice materials, microarchitected materials, microlattice, foam, honeycomb, additive manufacturing

Abstract

Additive manufacturing enables fabrication of materials with intricate cellular architecture, whereby progress in 3D printing techniques is increasing the possible configurations of voids and solids ad infinitum. Examples are microlattices with graded porosity and truss structures optimized for specific loading conditions. The cellular architecture determines the mechanical properties and density of these materials and can influence a wide range of other properties, e.g., acoustic, thermal, and biological properties. By combining optimized cellular architectures with high-performance metals and ceramics, several lightweight materials that exhibit strength and stiffness previously unachievable at low densities were recently demonstrated. This review introduces the field of architected materials; summarizes the most common fabrication methods, with an emphasis on additive manufacturing; and discusses recent progress in the development of architected materials. The review also discusses important applications, including lightweight structures, energy absorption, metamaterials, thermal management, and bioscaffolds.

1. INTRODUCTION

Nature evolved architected cellular materials for many situations in which low density as well as high stiffness and strength are needed. Examples are beaks and bones of birds that consist of thin, solid skins attached to a highly porous, cellular core (**Figure 1**). The architecture of the core is complex, with intricately shaped ligaments and gradients in density. Although humankind has developed synthetic materials, such as metal alloys, that are superior to the biological base materials, the cellular architectures developed by humans are much less sophisticated than nature's. Foams and honeycombs are the architectures used almost exclusively today because they can be readily manufactured, although they are far from ideal for many applications. The emergence of additive manufacturing technologies enables fabrication of cellular materials with more complex architectures, and many novel architected materials have been created over the last few years. In parallel, computational power and computational methods have improved enough to enable design of materials and structures with complex cellular architecture optimized for specific applications.

2. ADDING ARCHITECTURE TO MATERIALS

Architecture has always played an important role in large, familiar structures such as buildings or wheels. The first wheels were made out of solid stone or wood and had no notable porosity. In contrast, modern bicycle wheels have a superior architecture in which more than 95% of the material has been replaced with air. In the latter case, excellent strength and stiffness are achieved despite the light weight because the spokes are loaded in tension, where their performance is

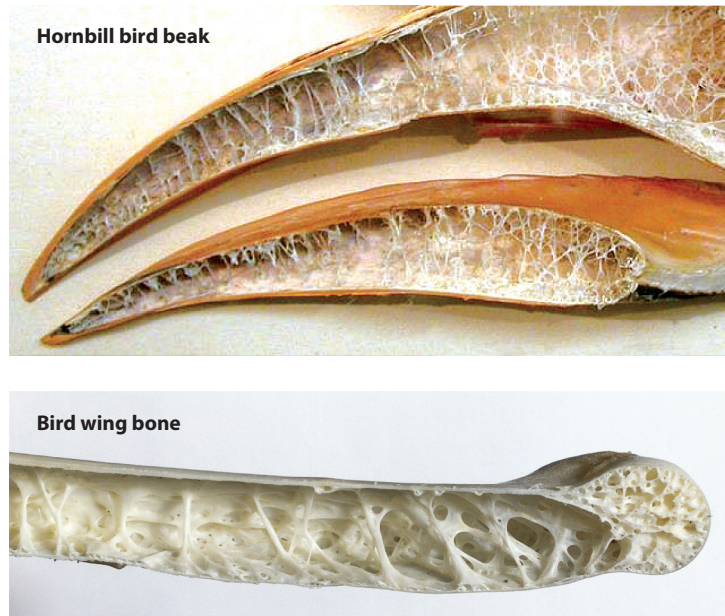


Figure 1

Architected cellular materials in the core of bird beaks and bones provide optimum strength and stiffness at low density. Additive manufacturing enables fabrication of materials with similarly sophisticated cellular architecture. Reproduced with permission from the Museum Natural History, London. Copyright © Trustees of the Natural History Museum, London.

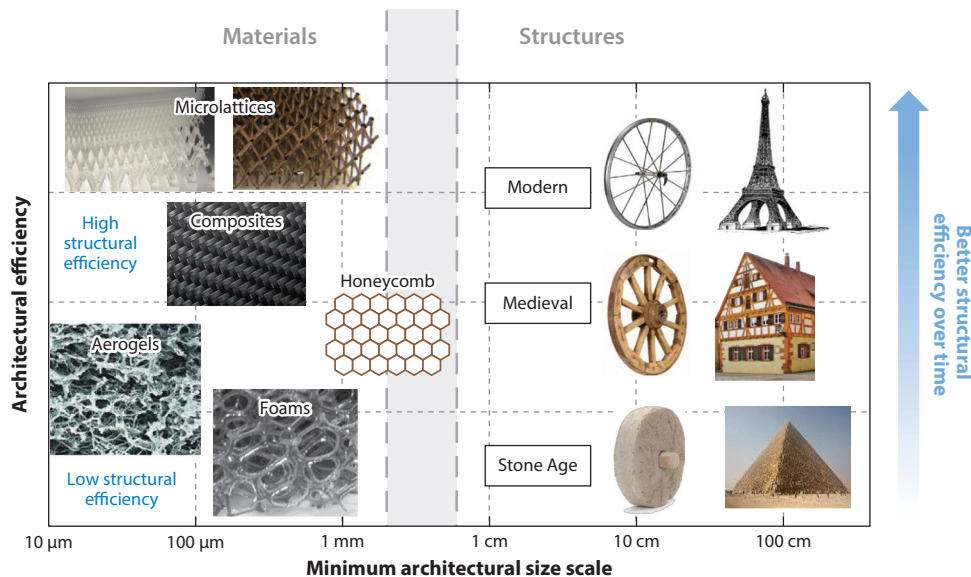


Figure 2

Bringing mechanical design to the material level. Engineering and architectural principles can now be applied at the material scale. Modern materials with complex architecture can achieve higher structural efficiency, such as in the case of modern buildings.

stretch dominated, and are not loaded in compression, where they would buckle and bend easily. The same concept is used to reduce the mass of materials in many weight-critical applications; for example, the cores of surfboards and rotor blades are not solid but are made from foam and honeycomb, respectively. The same engineering and architectural principles that have been used to increase the mechanical efficiency of structures can be applied at the material scale (**Figure 2**). Modern materials with complex architecture can achieve higher structural efficiency (1). Furthermore, architecture provides an additional degree of freedom in the design of a material. **Figure 3** shows general scenarios for adding architecture to materials (2). Additive manufacturing offers the opportunity to tailor the architecture to location-specific requirements. By varying cellular architecture, material properties can be altered throughout a part in such a way that the target application is maximally enabled. Powerful computational tools to optimize structures for mechanical efficiency allow the most structurally efficient and lightweight architecture for a complex load case to be computationally determined, and with the rapid progress in additive manufacturing, the limits on what can be made are dwindling. Additional progress must still be made to enhance the scale, throughput, reliability, and palette of available materials for broad commercialization.

3. MECHANICS OF ARCHITECTED MATERIALS

The properties of cellular materials are determined not only by the solid constituents but also by the spatial configuration of voids and solids—that is, the cellular architecture. The random cellular architecture of foams and aerogels results in bending-dominated deformation of the ligaments, resulting in a rapid decrease in strength and stiffness as porosity is increased. In contrast, certain ordered lattice-type cellular architectures can have nearly optimal stretching-dominated properties, resulting in materials in which the strength and stiffness scale proportionally with the


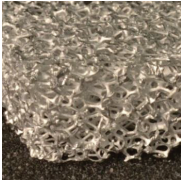
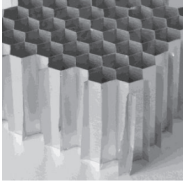
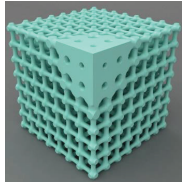
				
Cellular architecture	None	Random	Ordered	Ordered and location specific
Properties	Continuous and homogeneous	Homogeneous at scales > cell	Homogeneous and highly anisotropic	Inhomogeneous and highly anisotropic
Design degrees of freedom	Solid constituent	Solid constituent, cell size	Solid constituent, cell size, and orientation	Cell size/shape, node topology, ligament shape, material...

Figure 3

Adding architecture to materials. Traditionally, the properties of materials have been altered by varying the microstructure and production process. Changing the cellular architecture, i.e., the spatial configuration of voids and solids, is a powerful additional route to desirable material properties. By varying architecture locally within a cellular material, properties can be tuned to location-specific requirements.

solid volume fraction of the material (3). The first comprehensive treatise of mechanics of cellular materials was provided in 1997 by Gibson & Ashby (4), who describe the mechanics of foams and honeycombs in detail. Various ordered cellular architectures with improved mechanical properties were studied shortly after (5, 6). Noteworthy is the octet truss lattice with ideal linear scaling of mechanical properties, the mechanics of which were first analyzed by Deshpande et al. (7). **Figure 4** illustrates the influence of cellular architecture on the scaling of mechanical properties. At very low densities, even small differences in scaling can have a large effect on strength and modulus. Foam and honeycomb, the conventional cellular materials, scale far from ideal. Foams exhibit poor scaling due to their bending-dominated architecture, whereas honeycombs exhibit linear scaling until the failure mode shifts from yielding to cell wall buckling (8). Honeycombs are highly anisotropic and exhibit very little strength and stiffness in the lateral directions. The octet truss can outperform both foam and honeycomb, but difficulties in manufacturing have limited application of such octet truss materials. Additive manufacturing offers new avenues to realize complex cellular architectures, including octet truss lattices.

Among all the possible structural applications of architected materials, cores for sandwich panels could be the most important one. Sandwich structures are widely used in lightweight design, especially in aerospace but also increasingly in sporting and automotive applications. Covering the surface of the architected material with a thin and stiff facesheet has implications for the material's mechanical properties. Sandwich panels are typically loaded in bending, which subjects the facesheets to compression and tension, whereas the core is loaded in shear (**Figure 5**). Wadley et al. (6, 9) have proposed, modeled, and fabricated several core architectures. The different architectures can be optimized for specific loads by identifying the failure modes and tailoring the architecture to suppress the performance-limiting mechanisms. Many natural materials (e.g., human bones) and human-made materials (e.g., fiber-reinforced composites) exhibit structure on more than one length scale. If the structural elements themselves have structure, structural hierarchy is present and can play a large part in determining the bulk material properties (10). Additive manufacturing enables the realization of structural hierarchy tailored for specific applications.

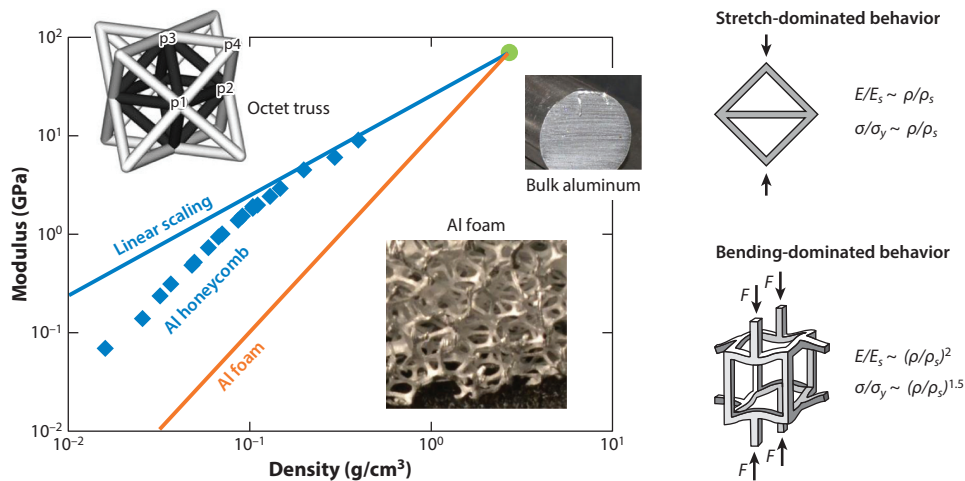


Figure 4

Influence of cellular architecture on the scaling of mechanical properties with density exemplified by aluminum foam, honeycomb, and octet truss.

4. EXTENDING MATERIAL PROPERTY SPACE WITH ARCHITECTURE

When the yield strength of all commercially available materials is plotted versus their density, an illustration of the material property space that can be readily analyzed is obtained (11) (**Figure 6**). White space in this material property plot signifies that no materials are available with this property combination. Especially at densities of less than 1 g/cm³, there are few options available—only foams, honeycombs, and some natural materials like balsa wood and cork.

By designing lattice structures, the property space of a known material can be extended. For example, fabricating nickel microlattices extends the property space that can be accessed with nickel (12) across a wide range of density, modulus, and strength. The intrinsic property of the constitutive material defines the upper bound because linear scaling with density is the best possible scenario (**Figure 7**). The architecture will define the extent to which the properties deviate from the ideal scaling. By fabricating lattice structures of extreme materials, such as diamond, fiber composites, and high-strength ceramics, white space can be accessed. As the ultimate material, diamond provides an outer bound of the theoretically attainable property space. By increasing porosity, the density can be decreased until the structural stability of the resulting material approaches zero (12) or until the pore size approaches levels that question the definition of a material.

Figure 8 shows some examples of white-space materials achieved through innovative cellular architecture. Alumina nanohoneycombs show record strength in the density regime around 0.7–1 g/cm³ (13). Ceramic silicon oxycarbide microlattices have also demonstrated white-space strength (14). By fabricating truss structures out of carbon fiber–reinforced polymer (CFRP) composites, white space can be accessed in strength and modulus versus density space (15, 16). Hollow nickel microlattices with a wide density range have been fabricated by varying cell size and wall thickness, and microlattices with densities as low as 0.9 mg/cm³ have been demonstrated (12, 17).

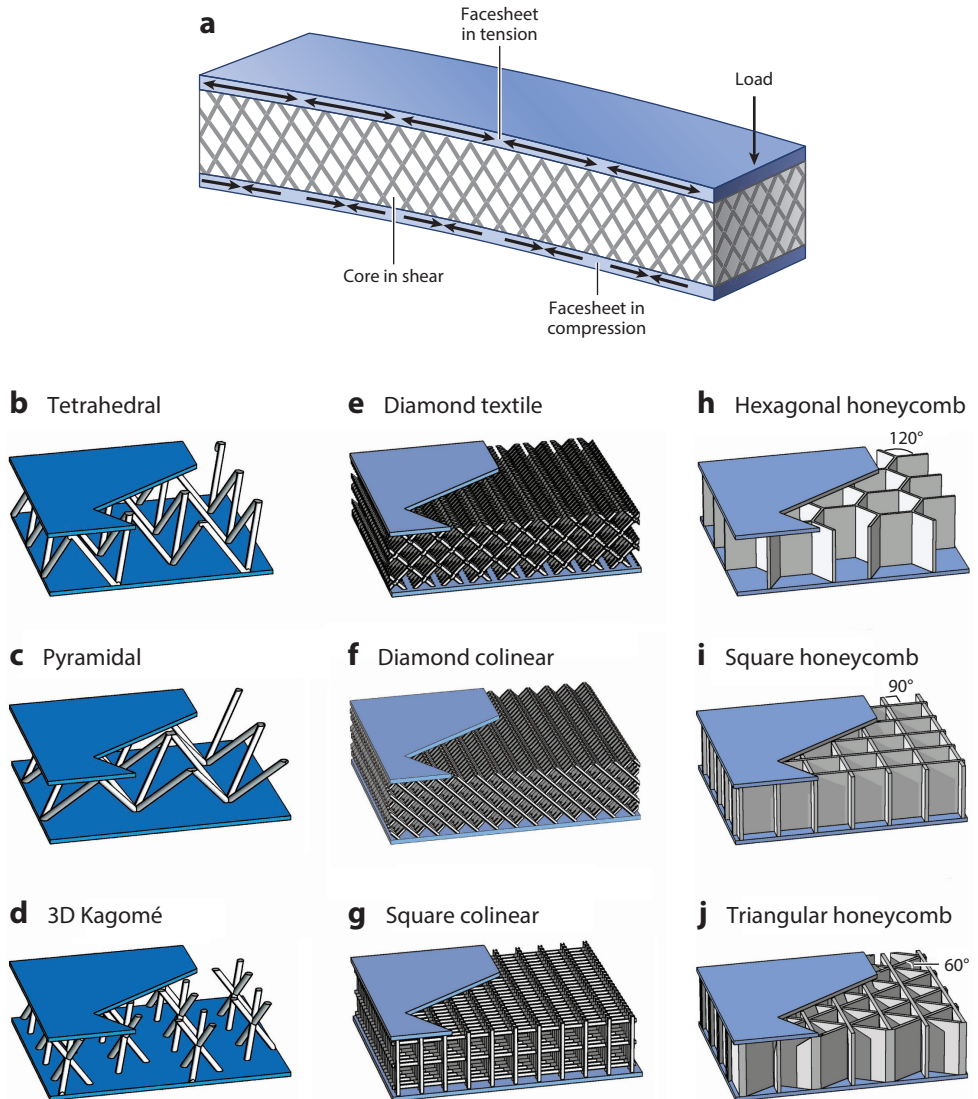


Figure 5

(a) Illustration of a sandwich structure commonly used in lightweight design under loading. (b–j) Examples of sandwich panels with periodic cellular metal cores. Panels b–j adapted with permission from Reference 9.

5. COMPUTATIONAL DESIGN AND OPTIMIZATION OF ARCHITECTED MATERIALS

With widely adjustable architectures, periodic cellular materials naturally lend themselves to optimization. In addition to selection of the ideal constitutive (base) material (or combination of materials in the case of a hybrid), multiple parameters of the cellular architecture (e.g., pore size, ligament diameter, ligament orientation) can be optimized for a specific objective or multiple objectives, subject to a number of constraints. A general procedure for optimizing architected materials can be summarized as follows (18):

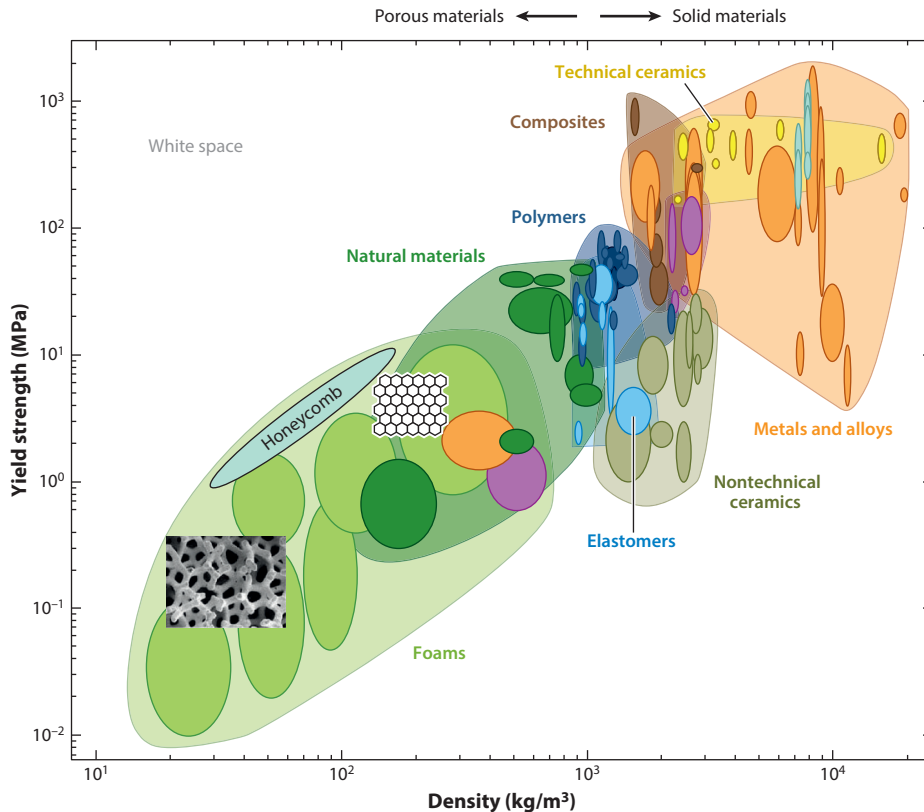


Figure 6

Material property space obtained by plotting yield strength versus density of all commercially available materials with the CES Selector database (11).

1. The fundamental properties of the base material(s) are chosen.
2. The variables of interest (e.g., strength, stiffness, heat transfer) are analytically modeled as a function of the architecture and the applied loads (e.g., mechanical, thermal).
3. The constraints for the application under consideration—including manufacturing constraints, geometric constraints (e.g., no buckling), and environmental constraints (e.g., no melting)—are formulated.
4. Numerical analyses are performed, for example, with commercial finite element packages, to verify the validity of the assumptions made in steps 2 and 3.
5. An objective function is established and then optimized with an optimization routine subject to the constraints established in step 3. Quadratic optimizers, such as *fmincon* (available in the MATLAB suite), are preferably used for convex problems, and discrete algorithms, such as genetic or particle swarm optimizers, are used for problems featuring many local minima.

To verify the optimization results experimentally, a prototype should be built and tested. Examples of optimizations with the above procedure include architected sandwich cores optimized for mechanical properties (19, 20) and active cooling (21). Integrating finite element analyses within the optimization loop can become very computationally intense and therefore remains a bottleneck in the optimization process. Ultimately, to take full advantage of the unique freedom in

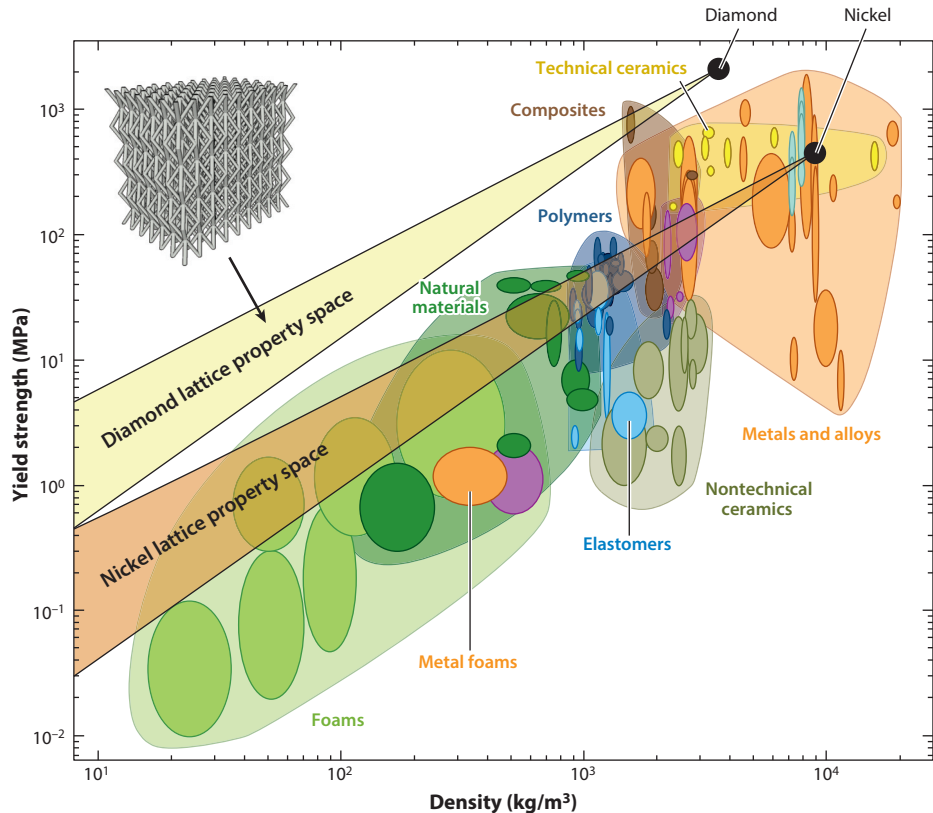


Figure 7

The property space of known material can be extended by designing lattice structures of that material.

designing with architected materials, the architecture itself should be a variable in the optimization process. Topology optimization algorithms have been developed to define the ideal arrangement of two or more materials to achieve optimum macroscopic properties (22, 23). To apply these algorithms to cellular materials, one material can be defined as air or void. To optimize structures for mechanical efficiency, powerful computational tools, for example, the commercially available software Altair OptiStruct (24) and Autodesk Within (25), were recently developed. With these tools, the most structurally efficient and lightweight architecture for a complex-shaped part and nontrivial load case can be computationally determined. A typical optimization starts with a solid part and removes material, whereby the user can choose to either achieve a favorable volume reduction, meet defined load requirements, or have a known displacement (26). The emerging additive manufacturing technologies now enable fabrication of such parts with fewer and fewer restrictions.

6. MULTIFUNCTIONAL OPPORTUNITIES THROUGH ARCHITECTURE

Architected materials offer unprecedented opportunities for multifunctionality (3). By tailoring the architecture, the properties can be varied to match location-specific requirements. **Figure 9**

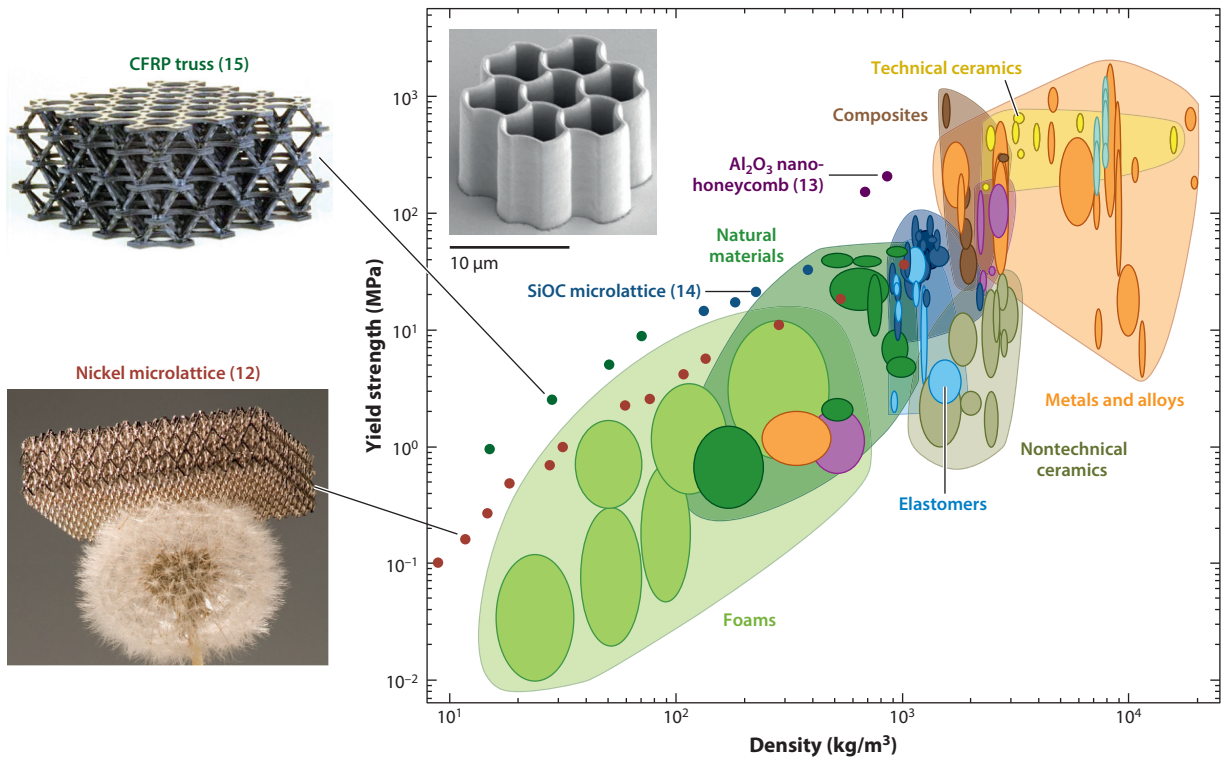


Figure 8

Examples of white-space materials realized by controlling cellular architecture. CFRP denotes carbon fiber–reinforced polymer.

shows a notional example: The relative density of the core of a wing can be varied by adjusting pore and ligament dimensions to increase strength where necessary (e.g., in areas exposed to higher air loads or impact), whereas the density is minimized in other locations to save mass. Additional functions can be addressed as well. For example, the core architecture can be tailored to ensure that the center of gravity is aligned with design targets, or the open cellular architecture can be optimized for thermal management. Another function that can be fulfilled by architected cellular materials is energy storage, specifically liquid fuel storage in open-celled porosity and chemical energy storage in structural batteries. Although such multifunctional requirements are not new in design, the recent advances in computation now enable optimization of an architected material to meet all desired objectives. In parallel, progress in additive manufacturing technologies enables realization of such complex materials with location-specific architecture.

7. ADDITIVE MANUFACTURING ENABLES ARCHITECTED MATERIALS

Materials with sophisticated cellular architecture can be fabricated with many approaches. The focus in this section is on additive manufacturing, with short remarks on other methods for the sake of completeness. Additive manufacturing is especially well suited for the fabrication of graded architecture. The technology has demonstrated the ability to fabricate architectures that are impossible to fabricate through conventional processing techniques. Although quality

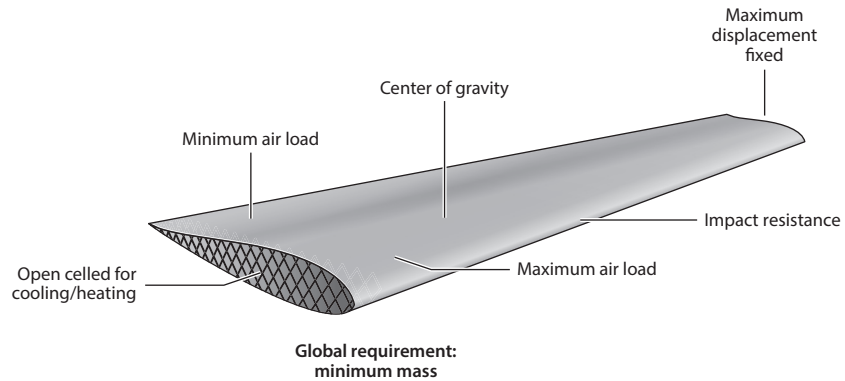


Figure 9

Multiple requirements can be fulfilled with a continuous architected material by tailoring the cellular architecture to local requirements.

and reliability of additive manufacturing processes are currently still questionable, in situ process monitoring should eventually enable extremely well controlled quality, zero failure rate, and rapid certification of additively manufactured architected materials (26). **Table 1** summarizes and compares the most common approaches to fabricating architected cellular materials, and selected techniques are described in more detail in the following sections.

7.1. Additive Manufacturing of Polymeric Architected Materials

The first additive manufacturing methods to mature were stereolithography (SLA), in which layers of liquid photopolymer resin are cured with UV light, and fused deposition modeling, in which thermoplastic polymers are extruded on a small scale. SLA offers a high resolution of approximately 25 μm and few constraints on geometry. Support structures are usually required for overhanging features (**Figure 10**). Fused deposition modeling is also a very flexible printing technology that is capable of dealing with small overhangs by using removable supports, similar to SLA. However, the resolution is typically lower than what can be achieved with SLA, and the available polymers are less strong. The layer-by-layer approaches result in stair steps at the surface that can have negative effects on properties (**Figure 10**). Several techniques have been developed to smoothen the surface of 3D-printed polymer parts (27). Separately processing every 50- μm layer results in long build times, typically 6–10 h for a 10-cm-high SLA part printed with a 50- μm resolution in the build direction. The long build time also increases the cost.

Two polymer-based additive manufacturing methods that transcend the limitations of layer-by-layer printing were recently developed. The first method, self-propagating photopolymer waveguide production, takes advantage of an optical effect that traps the UV light in a waveguide if the index of refraction changes on polymerization (28). With this method, layers of 2-cm thickness and more can be grown in one short exposure (1–2 min), 100–1,000 times faster than through traditional layer-by-layer methods. However, only features extending linearly from the exposure surface can be grown, which bodes well for lattice materials. The second method, continuous liquid interface production, uses digital image projection to expose the resin at a persistent liquid interface (29). With this method, one can generate monolithic polymeric parts with up to tens of centimeters in size and with a resolution of less than 100 μm at speeds 25–100 times faster than through conventional layer-by-layer methods. To decrease the density or to change the base

Table 1 Comparison of fabrication approaches for architected materials. Approaches are listed at the top, with decreasing maturity from left to right

	Fused deposition modelling	Selective laser melting (metals and polymers)	Electron beam melting	Polyjet printing	Stereolithography (including projection stereolithography)	Binder printing/jetting	Two-photon stereolithography	Wire or textile layout	Deformed perforated sheet lattice	Photopolymer waveguide	Projection microstereolithography	Electrophoretic deposition	Direct ink writing
Unit cell type	3D periodic or aperiodic	3D periodic or aperiodic	3D periodic or aperiodic	3D periodic or aperiodic	3D periodic or aperiodic	3D periodic or aperiodic	3D periodic or aperiodic	3D periodic	3D periodic	3D periodic or aperiodic	3D periodic or aperiodic	Quasi-3D	Quasi-3D
Arbitrary geometry	Yes with support structure	Yes with support structure	Yes with support structure	Limited angles	Limited angles	Yes	Yes	Bonded wires only	Limited to lattice cores	Limited to extended lattices	Yes	Limited to quasi-planar structure	Yes with support structure
Material diversity	Thermoplastic only	Select metals and polymers	Select metals	Select polymers	Select polymers	Metals, ceramics, polymers	Select polymers	Metals and polymers	Metals and select polymers	Photopolymers, preceramic polymers	Photopolymers and composites with nanoparticles	Metals, polymers, ceramics	Metals, polymers, ceramics
Mixed materials in part	No	No	No	Limited to polymers with varying properties	No	No	No	Limited to wire forms	No	No	Limited	Yes	Yes
Potential for graded properties	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Limited	Limited	Yes	Yes	Yes	Yes
Minimum feature size	~250 μm	~50 μm	~200 μm	~100 μm	~2.5 μm	~100 μm	~150 μm	~10 μm	~100 μm	~5 μm	~1 μm	~1 μm	~500 μm
Fabrication area	~0.5 m^2	~0.2 m^2	~0.2 m^2	~0.2 m^2	~0.2 m^2	~0.5 m^2	~0.005 m^2	~0.1 m^2	~1 m^2	~0.5 m^2	~0.03 m^2	~0.05 m^2	~0.1 m^2
Fabrication height	1 m	30 cm	30 cm	30 cm	30 cm	30 cm	1 cm	10 cm	10 cm	2 cm	<1 cm	<1 cm	5 cm
Application performance	Prototypes	Robust final parts	Robust final parts	Prototypes	Prototypes	Prototypes	Research materials	Research materials	Research, prototypes	Research, prototypes	Research materials	Research materials	Prototypes
Production rate	Medium (single parts)	Low (single parts)	Low (single parts)	Low (single parts)	Low (single parts)	Low (single parts)	Very low	Medium	High	High	Low	Medium	Medium

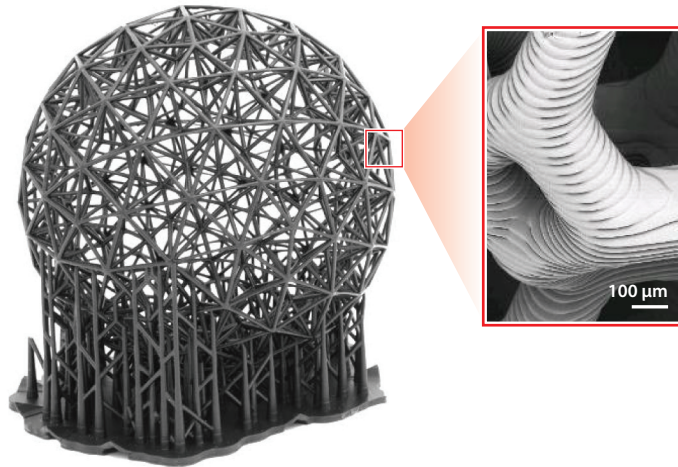


Figure 10

Architected polymer structure 3D printed via stereolithography. The inset shows the steps in the surface caused by the layer-by-layer printing process. Figure adapted with permission from Formlabs, Inc.

material, thin films or coatings can be deposited onto 3D-printed polymer materials, which are subsequently removed with a polymer etch, as discussed in more detail in Section 7.5.

Two-photon lithography enables 3D printing of polymers at a much higher resolution than that achieved through standard SLA. A 3D laser lithography system offered by Nanoscribe GmbH (Germany) can achieve a resolution down to 150 nm. Such resolution enables the fabrication of architected materials at the nanoscale, for example, lattices with a 10- μm cell size coated with a 20-nm, thin ceramic film via atomic layer deposition (13, 30). Such nanolattices exhibit increased strength caused by nanoscale effects. At a thickness of 20 nm, the ceramic shell approaches its theoretical strength because the probability and size of a possible flaw are greatly reduced (31, 32).

7.2. Additive Manufacturing of Metallic and Ceramic Architected Materials

Three main approaches for additive manufacturing of metals lend themselves to manufacturing of architected materials: metal powder bed fusion, directed energy deposition, and binder jetting. In powder bed fusion, the most successful method in the market, the metal powder is typically melted with either a laser or an electron beam (33). These processes can produce parts that have 50–100- μm resolution and that approach 100% density (27). Residual porosity in additively manufactured metal materials compromises toughness and fatigue properties. Due to the rapid cooling rates during the solidification of the small melt pool, very fine grained microstructures are achieved. Custom microstructures that cannot be achieved with traditional processes have been created, and in some cases such structures show significantly improved strength and ductility relative to the properties of cast material.

Cellular materials, such as lattice structures, can easily be fabricated by metal powder bed fusion (34, 35) (**Figure 11**). Physical properties can readily be tailored by varying the cellular architecture or base material properties. For example, by changing electron beam parameters (beam current, beam speed, and beam focus), the elastic modulus and yield strength of Inconel 625 mesh cubes have been systematically varied by approximately a factor of ten (36).

Directed energy deposition approaches such as laser-engineered net shaping or freeform welding can be used to 3D print large structures. One example is a bridge with numerically optimized

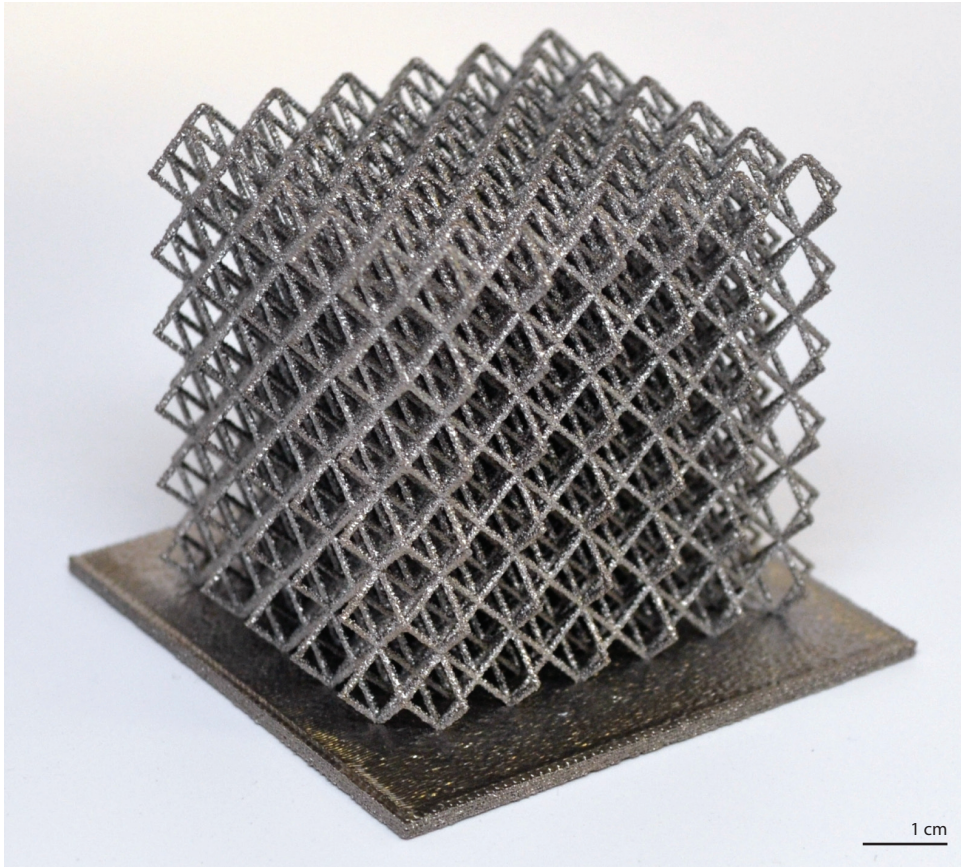


Figure 11

Ti-Al6-V4 lattice material fabricated via electron beam melting (by CalRAM, Inc., for HRL, LLC).

architecture printed out of steel with a multiaxis printer that combines a metal inert gas welding machine with a robotic arm by the company MX3D in Amsterdam, Netherlands.

The advances in additive manufacturing have also led to a multitude of different techniques for ceramic materials. Among the many commercially available 3D printing systems, a few offer printing of ceramics either by selective curing of a photosensitive resin that contains ceramic particles, by selective deposition of a liquid binder agent onto ceramic particles (binder jetting), or by selective fusion of a powder bed with a laser (37, 38). Due to the high melting point of ceramics, consolidation of powder to a dense part poses a larger challenge than this process would be for metals, and residual porosity is typically unavoidable (39). Furthermore, many additive processes that use energy locally introduce cracks through thermal gradients. Pores and cracks are responsible for the low strength and poor reliability of additively manufactured ceramic parts.

7.3. Assembly of Architected Materials

Various approaches have been developed to assemble architected cellular materials from building blocks. One example is a CFRP lattice that is made using a snap-fit assembly technique whereby 2D building blocks of [0/90] CFRP laminate are assembled into a 3D lattice. This lattice has excellent

mechanical properties because half the fibers are always oriented along the trusses to maximize both their elastic stiffness and compressive/tension strength (15). The snap-fit connectors can be designed so that the assembly can be reversible (16). Similarly, metallic lattices can be assembled from building blocks that are machined (40) or from solid metal sheets that are perforated and folded (41), followed by brazing or diffusion bonding to ensure strong connections. A related method for creating complex 3D materials and structures combines direct-write assembly with a wet-folding origami technique whereby planar lattices are printed and then folded, rolled, or molded into the desired shape (42).

7.4. Weaving, Braiding, and Knitting of Architected Materials

Fibers and wires of many different materials are readily available and offer high stiffness and strength. Such fibers and wires bode well for creating cellular materials by weaving, braiding, and knitting. 3D metallic lattices are woven with metallic wires, such as Cu or Ni wires, and the wire nodes are bonded with a soldering technique to provide stiffness (43). Similarly, lattice materials can be braided and the wire intersections can be fixed by vapor-phase alloying techniques such as vapor-phase aluminiding or chromiding (44). Furthermore, 3D knitting can be fully automated and has recently enabled innovative new products such as flyknit footwear introduced by Nike, Inc. (45). Although the architectures that can be achieved by weaving, braiding, and knitting are somewhat limited, select base materials, such as carbon fibers, offer mechanical properties that cannot be achieved with 3D printing.

7.5. Converting Thin Films into Architected Materials

Architected materials based on a broad range of thin-film materials can be fabricated by coating polymer templates. The polymer templates, typically lattice materials consisting of interconnected struts, can be formed by one of the additive manufacturing methods described in Section 7.1. A thin-film material is then deposited onto the polymer template, and the template is subsequently removed by chemical etching. With this approach, architected materials constructed from hollow ligaments can be fabricated from a wide variety of metals, polymers, and ceramics. In principle, any thin-film material can be converted into a 3D lattice material with this approach, provided that there is a non-line-of-sight deposition process, sufficient etch selectivity, and sufficient film cohesion, offering an exciting expansion of available cellular materials. Hollow microlattices have been fabricated out of several thin-film materials, including nickel and copper via electroless plating, gold via electron beam physical vapor deposition, parylene polymer via chemical vapor deposition, and silicon dioxide via atomic layer deposition (**Figure 12**). The fabrication process allows control over three levels of structural hierarchy spanning three orders of magnitude: the hollow tube wall (with thickness approximately on the nanometer to micrometer scale), the hollow tube lattice member (with diameter approximately on the micrometer to millimeter scale), and the lattice unit cell (with distance between adjacent lattice members approximately on the millimeter to centimeter scale). These parameters of the microlattice cellular architecture can be optimized for a given application, e.g., heat exchangers, sandwich panel cores, battery electrodes, catalyst supports, and acoustic, vibration, and shock energy absorbers (12, 46). Special consideration must be given to the surface of the 3D-printed templates, as steps from the printing process become undulations in the walls of the struts. If these undulations are on the same order of magnitude as the wall thickness, they can constitute initiation sites for deformation, thereby resulting in a prebuckled state with detrimental effects on strength.

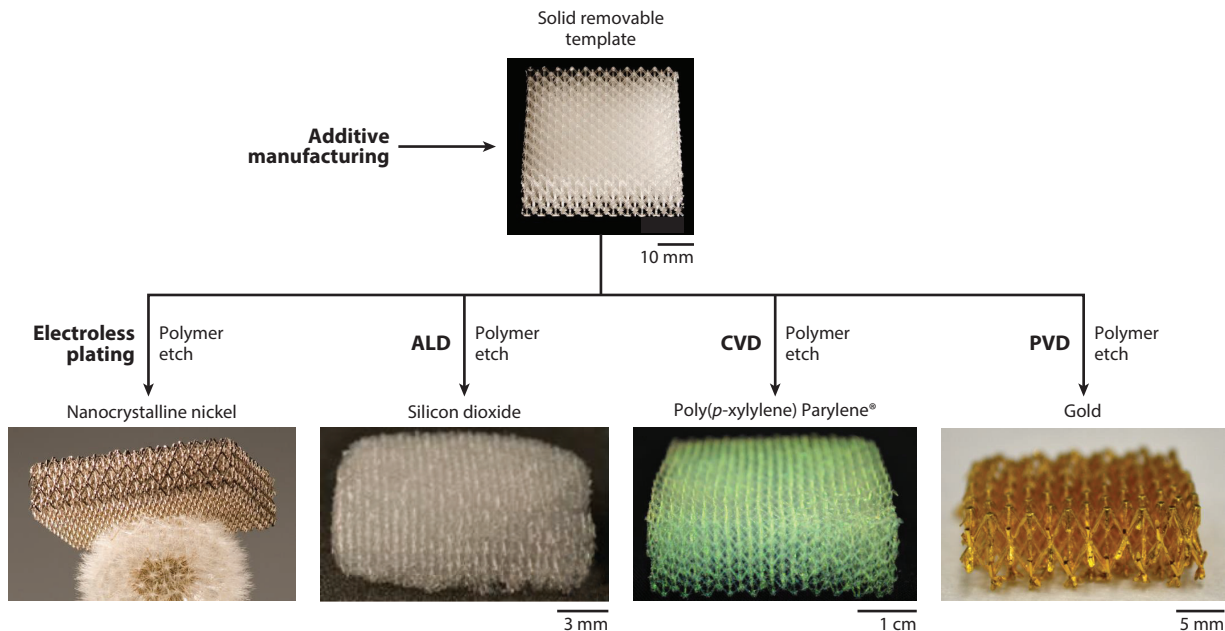


Figure 12

Various 2D thin-film materials can be converted to 3D architected materials by depositing them on a template that is subsequently removed. Abbreviations: ALD, atomic layer deposition; CVD, chemical vapor deposition; PVD, physical vapor deposition.

8. APPLICATIONS

8.1. Architected Materials for Lightweight Structures

In most cases in which architected cellular materials are bearing a load, facesheets are attached to the outward-facing surfaces. By attaching thin, stiff facesheets to the top and bottom surfaces of a relatively thick, lightweight core, mechanically efficient, lightweight sandwich panels that are widely used in the aerospace industry can be created. The thickness of the core separates the facesheets, thus providing the structure with a high area moment of inertia. In a sandwich structure, the facesheets carry in-plane and bending loads, whereas the core carries transverse shear and transverse compression loads. The honeycomb cellular architecture is the current state-of-the-art sandwich core; aluminum alloys, aramid fiber paper (Nomex[®]), and glass fiber–reinforced polymer represent the most common constituent materials. Closed-cell polyurethane or PVC foam is an alternative with generally lower performance (2). More recently, alternative core materials have been studied, among which the most compelling are tetrahedral and pyramidal truss structures (4). Hollow truss structures, when designed to suppress buckling, offer an opportunity for improved compressive and shear strengths relative to honeycombs (47, 48).

Using additive manufacturing techniques for the cores of sandwich structures offers several advantages over conventional honeycomb or foam manufacturing, including the ability to form net-shape cores, cores with complex curvature, and cores with graded cellular architectures. Hexagonal honeycomb panels are difficult to fit to a curvature due to their anticlastic behavior (8) and must be machined to shape out of large blocks, adding manufacturing cost. The complexity of lightweight structures continues to grow with ever-increasing structural, aerodynamic, and packaging requirements. Therefore, performance and weight benefits may be achieved using complex-shaped

sandwich cores with spatially graded properties. By designing a core that has a location-specific density that is matched to the local loads, substantial weight savings can be realized over conventional cores with uniform density and properties that must be selected to match the highest local load. Additively manufactured truss cores can easily be tailored by varying the cellular architecture. A problem specific to honeycombs is that moisture is easily trapped in the closed cells, which increases weight and shifts the center of gravity, an effect that can be mitigated by open-celled cores. Lastly, additively manufacturing cores, or coating 3D-printed core templates, widens the available base material palette. **Figure 6** shows some examples of sandwich panels with periodic cellular cores.

8.2. Architected Materials for Energy Absorption

Energy-absorbing materials are of broad interest for protection from impacts and shockwaves in applications ranging from helmets to vehicles and sporting gear. For protection, an intervening medium is required that is capable of a large volume decrease to reduce the incoming pressure below a damage threshold and thereby extend the impulse duration. Dense solids and fluids are not suitable, because they are incompressible, and therefore cellular materials are sought (49).

Depending on the application, different performance characteristics are required of the energy-absorbing material. A general distinction can be drawn between single-use and multiuse applications. For multiuse applications, a material is required that can recover from the deformation, such as an elastomer foam. For single-use applications, plastic deformation can absorb the energy, and metallic materials can be used. The damage threshold or injury criterion determines the maximum allowable stress transmitted through the energy absorber. For energy absorbers in direct contact with the human body, the injury criterion is generally on the order of 1 MPa. Space limitations and light weight considerations typically call for a material with maximum energy absorption per unit volume and unit mass. These requirements call for a stress-strain performance with maximum modulus E , a constant crushing stress just below the injury criterion, and a maximum densification strain. However, actual energy absorption materials fall short of this ideal response. **Figure 13** shows the performance of a range of energy absorption materials. Extruded polystyrene foam and extruded polypropylene foam are the standard energy absorption materials currently used for helmets and sporting gear. Architected materials present a new class of energy absorption materials that offer more flexibility in tailoring the response to impulsive loads than conventional materials can. **Figure 13** shows several examples of conventional energy absorption materials—specifically extruded polystyrene foam, open-cell aluminum foam (Duocel[®]), and virgin and precrushed aluminum honeycomb (Hexcel[®])—as well as examples of energy absorption materials with more complex architecture: solid aluminum microlattice with octahedral architecture, thermoplastic polyurethane twin hemispheres (Skydex[®]), and hollow nickel microlattice with vertical posts (50). Hollow-sphere materials also offer good energy absorption (51), and their application as energy absorbers in a crash box and a B-pillar of a passenger car has been investigated (52). As deeper understanding of injury biomechanics is developed, more sophisticated protection materials will be sought to address complex injury criteria. Further optimization of cellular architecture, guided by numerical modeling, will result in the next generation of energy absorption and protection materials.

Beyond the applications discussed above, energy absorption materials are employed for acoustic and vibration damping. This is another field in which architected materials enabled by additive manufacturing could have a big impact. One example is hollow-sphere structures in which the spheres are partially filled with granular material (53).

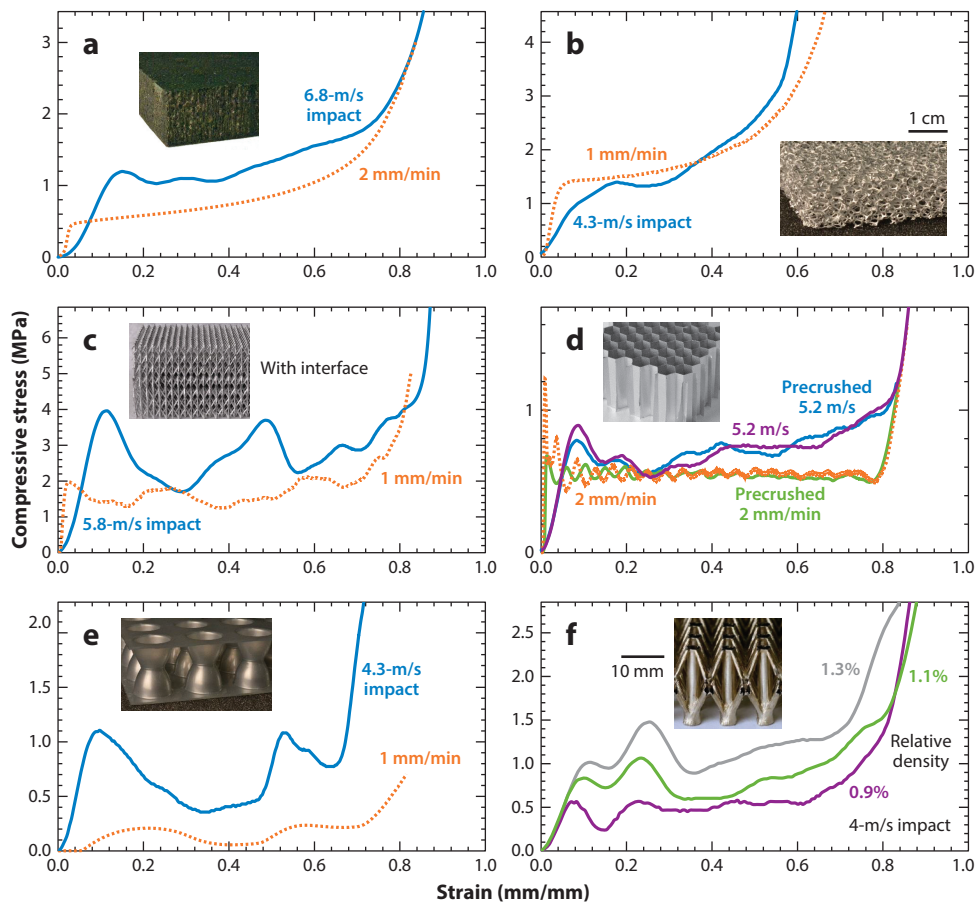


Figure 13

Compressive response of energy absorption materials: (a) extruded polystyrene foam, (b) open-cell aluminum foam (Duocel[®]), (c) solid aluminum microlattice, (d) virgin and precrushed aluminum honeycomb (Hexcel[®]), (e) thermoplastic polyurethane twin hemispheres (Skydex[®]), and (f) hollow nickel microlattice with vertical posts. Materials in panels a, c, d, and e are 2.54 cm (1 inch) thick.

8.3. Architected Materials for Metamaterials

Architected materials are a class of materials for which cellular architecture defines the properties in addition to chemistry and microstructure. Above, this review considers mostly mechanical properties, although the same concept can be applied to properties that are defined by wave phenomena. This has historically been the field of metamaterials. More recently, the term mechanical metamaterial has been used to describe architected materials with uncommon mechanical properties (54). Although this review is not intended to set definitions, it is suggested that metamaterials fall within the larger group of architected materials. The field of metamaterials has been dealing with electromagnetic waves for two decades (55). Photonic crystals, the classic metamaterial, exhibit a periodic microstructure with a unit cell small enough to affect electromagnetic wave propagation in the same way that the periodic potential in a semiconductor crystal affects electron motion by defining allowed and forbidden electronic energy bands. By designing a subwavelength unit cell from existing constituent materials and periodically arranging it into a lattice, the global

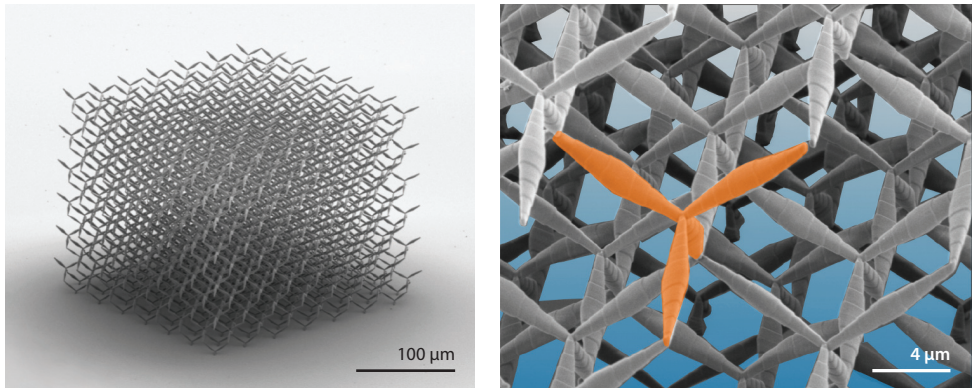


Figure 14

Pentamode metamaterials almost behave like fluids. The stable four-leg structure (shown in *orange*) is the basic element of the pentamode metamaterial. These materials were proposed years ago but could only recently be realized, by additive manufacturing. Figure adapted from and courtesy of Center for Functional Nanostructures, Karlsruhe Institute for Technology.

properties are then determined by the architecture, rather than by the chemistry. By tailoring the architecture, the properties of the metamaterial can be changed, and unprecedented properties can be achieved. Photonic crystals have demonstrated fascinating properties, including negative phase velocities of light, invisibility cloaking, and unusual optical nonlinearities (56). However, this concept can be applied to a range of wave phenomena beyond optics. Promising are thermal, acoustic, elastic, or irreversible nonlinear mechanical properties. The corresponding wavelengths and length scales range from tens of micrometers to centimeters, as opposed to the length scale of nanometers in optics, and therefore fabrication limitations are relaxed, thus easing real-world applications (56, 57). Additive manufacturing offers many opportunities for fabricating metamaterials. Pentamode metamaterials are a good example: Proposed years ago, they have been realized only recently by dip-in laser writing, a method derived from direct laser writing developed by the Nanoscribe company (58) (**Figure 14**). Pentamode metamaterials have close to zero shear modulus, similar to a fluid, and open new possibilities in transformation acoustics.

Mechanical metamaterials that exhibit reversible deformation enabled by their architecture rather than by their constituent materials have been demonstrated. Microlattices based on extremely thin-walled hollow tubes buckle on loading and spring back on unloading independently of the constituent material (46). **Figure 15** shows this effect in microlattices formed from brittle, nanocrystalline nickel (12), and similar behavior has also been observed in ceramic nanolattices (30). The microlattice in **Figure 15** also shows auxetic behavior, which implies a negative Poisson's ratio. Auxetic materials are another class of mechanical metamaterials that are now being realized via additive manufacturing, for example, reentrant honeycomb structures (59). Guided by theoretical and numerical analysis, researchers can exploit material and geometric nonlinearities to design novel materials with tunable properties, such as negative-Poisson's-ratio behavior induced by an elastic instability (60). Spatial manipulation of elastic waves can also be achieved with architected materials (61). Similarly, acoustic waves can be manipulated, leading to interesting acoustic effects. A practical low-loss acoustic cloak for underwater ultrasound was recently realized (62). This metamaterial cloak is constructed with a network of acoustic circuit elements, namely serial inductors and shunt capacitors that are realized as subwavelength cavities, and has connecting channels with spatially tailored geometry. By machining a planar network of these elements in



Figure 15

Mechanical metamaterials can achieve unique properties. A metallic microlattice shows reversible deformation and auxetic behavior.

an aluminum plate, the acoustic cloak can effectively bend ultrasound waves with a frequency of 52 to 64 kHz around a hidden object, with reduced scattering and shadow in 2D (62). Additive manufacturing opens up the possibility of fabricating arrays of such acoustic circuit elements in 3D. Other examples include thermal metamaterials, and a freespace, omnidirectional, broadband thermal cloak was recently demonstrated (63). This cloak can protect objects from overheating transiently while maintaining the same downstream heat flow as without object and cloak.

8.4. Architected Materials for Thermal Management

Cold plates, heat pipes, and heat exchangers are of paramount importance for thermal management, especially high-performance cooling. Architected cellular cores enable designs with improved performance, especially when one wishes to optimize multiple objectives, such as maximum heat transfer rate, minimum pumping energy input, minimum temperature drop, and minimum mass (**Figure 16**). Small feature size on the microscale is often required due to space limitations but also has inherent advantages because heat transfer per unit area scales inversely with characteristic channel width and because the surface area-to-volume ratio increases with decreasing device size, enabling enhanced efficiency per unit volume (64).

A typical cold plate or heat sink consists of serpentine metal tubing through which the coolant flows; the tubing is pressed into a channeled aluminum plate or is inserted into drilled holes. To increase heat transfer and mitigate flow nonuniformities across the entire cold plate, a porous medium can be inserted into the coolant pathway. This porous medium can take many geometric forms, such as plate fins, pin fins, louvered fins, sintered beds (65), reticulated metal foams (66), and prismatic and truss structures (67). Valdevit et al. (21) compared different heat sink technologies and showed that periodic structures, e.g., prismatic or truss cores, show better cooling performance than do textiles and foams (**Figure 16a**). For multifunctional applications, the mechanical properties, e.g., bending stiffness, compressive strength, and shear strength, of cold plates are of importance. Periodic lattice structures generally exhibit better mechanical performance than do random foams or unidirectional fins (5).

Planar heat pipes contain both an open-celled core that allows for vapor flow and a porous wick that transports the liquid. Heat pipes have been developed from a variety of cellular materials (68). The architecture of the cellular materials can be optimized for multiple objectives (69), and vapor-venting arterial wicks can provide enhanced performance.

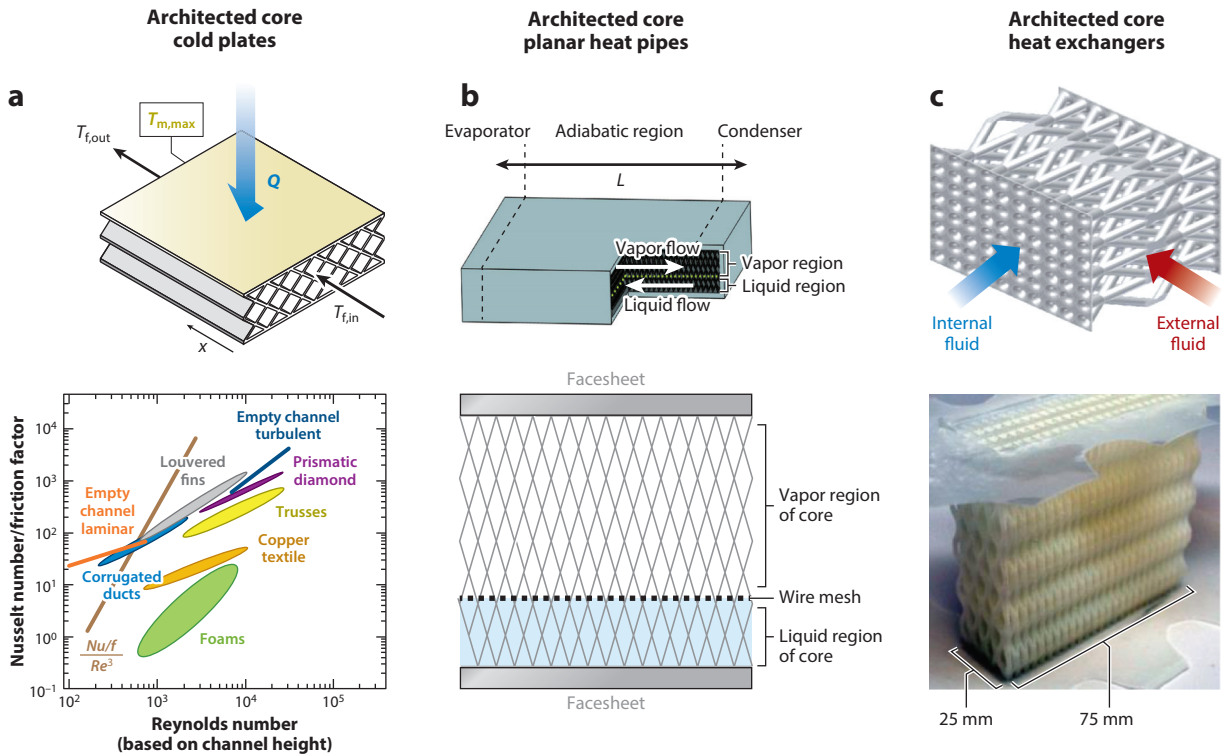


Figure 16

The performance of (a) cold plates, (b) heat pipes, and (c) heat exchangers can be improved by introducing architected cellular cores enabled by emerging additive manufacturing techniques. Adapted with permission from References 21 (panel a), 69 (panel b), and 72 (panel c).

Heat exchangers have been fabricated from various cellular and periodic materials (67, 70). Advanced devices exhibit two separate fluid paths in each cell, realizing cross-flow heat exchangers with enhanced heat transfer (71). Additive manufacturing has enabled fabrication of such cross-flow heat exchangers with optimized cellular architecture. One fluid path is printed via SLA or related methods. Next, the resulting structure is coated, and the printed polymer template is removed, opening up the fluid path that is now enclosed by the coating. Manifolds can be integrated during the 3D printing or coating step (72) (**Figure 16**). Synergies between maturing additive manufacturing techniques and simulation techniques for mechanics and fluid flow of architected materials are expected to lead to cold plates, heat pipes, and heat exchangers with improved performance.

8.5. Architected Materials for Bioscaffolds

Architected materials can also be applied as bioscaffolds to repair and replace tissue, cartilage, and bone. All bioscaffolds need an interconnected pore network for cell growth and flow transport of nutrients and metabolic waste (73). Additive manufacturing is highly advantageous because it offers the possibility of rapidly producing bioscaffolds meeting a patient's specific requirements in terms of tissue defect size and geometry as well as biological features (74). In addition to requirements such as biocompatibility and suitable surface properties for cell attachment, bioscaffolds must

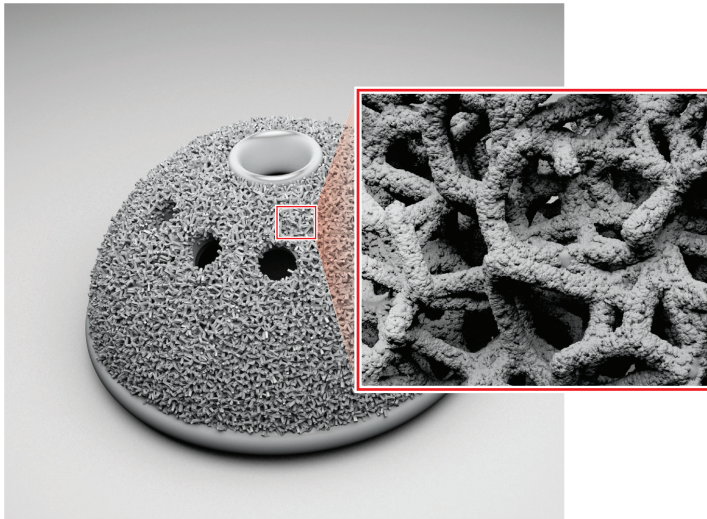


Figure 17

Hip implant featuring trabecular lattice designed to encourage bone ingrowth. Adapted with permission from Autodesk Within Medical (Reference 25).

typically match the mechanical properties of the tissues at the site of implantation. Therefore, the architecture needs to be optimized for mechanical and fluid transport properties.

Several bioscaffolds for repair or replacement of tissue are commercially available and support cellular repopulation and revascularization by the host tissue (75). Although these scaffolds are currently derived from human or animal tissue, efforts are under way to synthesize bioscaffolds that mimic the complex porous architecture, for example, by electrospinning cellulose acetate (76) or alginate coating of bioglass foam (77).

Architected materials are also used to facilitate osseointegration: the ingrowth of bone into an implant. A case study by Within Labs transformed an existing hip implant design to one with superior qualities that may aid osseointegration while maximizing the inherent benefits of additive manufacturing (25). The trabecular lattice featured in **Figure 17** is designed with these objectives.

9. CONCLUSIONS

We review above the status of the field of architected cellular materials. The recent advances in additive manufacturing are giving a boost to the field of architected materials. As new methods emerge and mature, fabrication of more and more complex cellular architectures is enabled, and costs are decreasing. Such developments will facilitate commercialization of several applications currently under research and development, and additional applications are bound to arise. New optimization techniques combined with increasing computational power is aiding the design of multiscale cellular architectures that fulfill multiple objectives. Therefore, the field of architected cellular materials is expected to yield more breakthroughs in the future.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

The authors gratefully acknowledge financial support from HRL Laboratories, LLC, and Defense Advanced Research Projects Agency under the Materials with Controlled Microstructural Architecture program managed by Judah Goldwasser (contract W91CRB-10-0305) and thank Jacob Hundley, Alan Jacobsen, Christopher Roper, Lorenzo Valdevit, and Sophia Yang for useful discussions.

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