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[Journal of Physics D] **Roadmap**

Manufacturing and Scale-up Roadmap for Metamaterials

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Abstract

Metamaterials provide exceptional properties arising from their well-defined engineered structures in which periodic features ranging from the nanoscale to the macroscale are manufactured to yield the desired characteristics. Recent advances in manufacturing techniques have dramatically expanded the design space and potential applications of metamaterials. Progress in high-resolution additive processes, scalable subtractive techniques, and emerging hybrid and formative approaches has enabled architectures that were previously difficult to realise at meaningful scale. Although challenges remain for scaling production, recent advances are moving metamaterials beyond laboratory-scale demonstrators towards more manufacturable platforms. These developments suggest emerging – though still early – pathways for broader technological deployment, enabling new possibilities for multifunctional devices, large-area metasurfaces, and mechanically robust architected materials. This roadmap explores the current-state-of-the art manufacturing techniques for metamaterials, highlighting key challenges and opportunities in scaling-up production and commercialisation, and outlines potential strategies for overcoming the barriers that currently limit large-scale implementation.

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1. Introduction

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Metamaterials are engineered materials with unique properties derived from their microstructural design rather than their intrinsic composition. These properties emerge from carefully designed geometries and the spatial arrangement of constituent materials across nano- to mesoscale dimensions [1]. Over the past decades, advances in computational design, multiscale modelling, and precision fabrication have enabled increasingly complex architectures across a broad family of metamaterials spanning mechanical, electromagnetic, and acoustic domains. More recently, the field has expanded to include active and reconfigurable metamaterials, offering programmable and adaptive functionalities. As a result, metamaterials are attracting growing interest across sectors such as aerospace, defence, healthcare, telecommunications, artificial intelligence, computing, and renewable energy [2].

A major challenge in realising metamaterials lies in the fabrication of their intricate, multiscale geometries. The first experimental demonstration of a metamaterial in 2001 – an electromagnetic metamaterial exhibiting a negative refractive index at microwave frequencies – was fabricated using conventional printed circuit board processes and consisted of copper strips and split ring resonators arranged in a periodic array [3]. Since then, significant progress in manufacturing techniques has enabled the fabrication of increasingly sophisticated architectures for mechanical, electromagnetic, and acoustic metamaterial applications. These developments are closely linked to the capabilities and limitations of different manufacturing processes, as summarised in figure 1, which compares the achievable resolution ranges of additive, subtractive and formative manufacturing techniques for metamaterials.

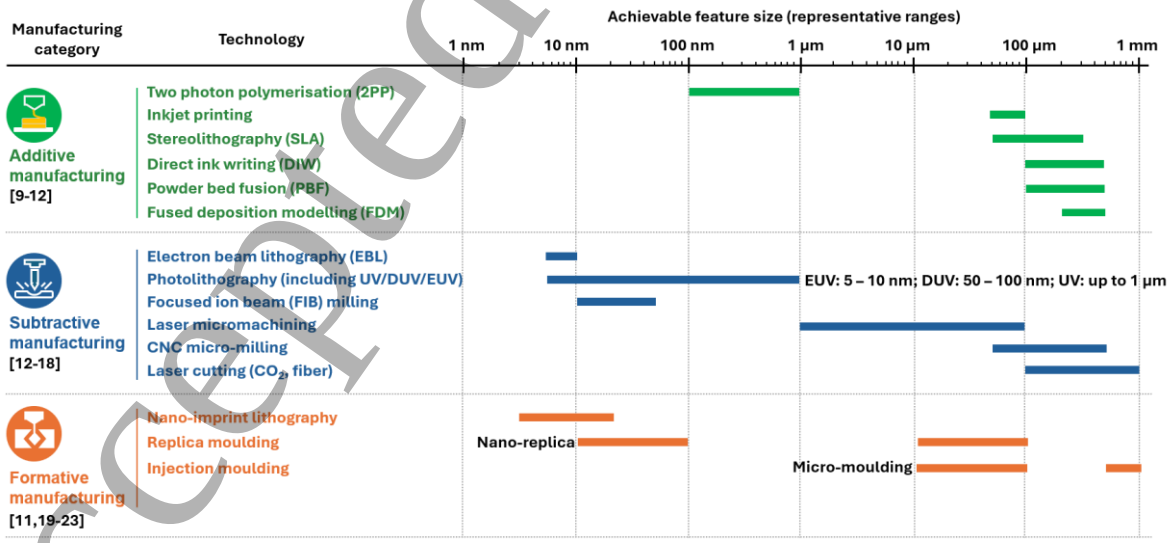


Figure 1. Comparison of achievable minimum feature sizes across additive, subtractive and formative manufacturing techniques for metamaterial fabrication. The ranges shown represent typical values reported in literature for representative systems and are intended to illustrate order-of-magnitude capabilities rather than fixed process limits. Actual feature sizes are strongly dependent on system configuration, material system and process conditions and may vary significantly between implementations.

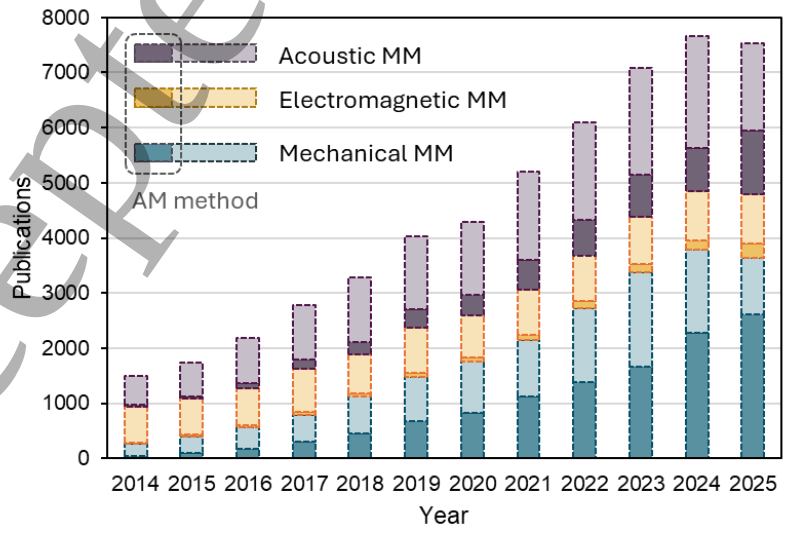
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Additive manufacturing (AM) has emerged as a particularly powerful approach, with high-resolution techniques such as two photon polymerisation and electrohydrodynamic jetting enabling nanoscale features, while micro- to mesoscale AM techniques are widely used for mechanical and acoustic metamaterials. Over the last decade, AM has played a crucial role in realising complex structures such as origami-inspired and auxetic metamaterials (figure 2). Subtractive manufacturing, which includes micromachining, lithography, etching, computer numerical control (CNC) machining, and laser cutting, provides capabilities for 2D, 2.5D and 3D architectures, with specialised tools such as focused ion beam (FIB) milling and electron beam lithography (EBL) enabling nanoscale patterning. Formative manufacturing approaches, such as nanoimprint lithography, replica moulding and injection moulding, enable the fabrication of 2D and 3D metamaterials across multiple length scales, with potential for scalable production [4].

Although widespread commercial deployment remains limited, several early successes demonstrate the emerging practical potential of metamaterials [5]. Electromagnetic metasurfaces have entered niche markets in beam-steering antennas, imaging, and optical security features [6]. Mechanical and acoustic metamaterials are beginning to appear in vibration-damping components, noise-control systems, and lightweight architected structures [7,8]. These examples, though modest in scale, signal a gradual shift from purely laboratory-scale towards application-driven development.

Despite this progress, manufacturing remains one of the most significant barriers to broader adoption. Many metamaterial designs require complex geometries, multiscale features or heterogeneous material combinations that challenge conventional manufacturing methods. Recent advances across additive, subtractive and formative manufacturing have begun to address these limitations, enabling higher throughput, improved fidelity, and larger-area production. Understanding how these techniques can be leveraged – and where critical gaps remain – is essential for guiding the next phase of metamaterial innovation.

This roadmap provides an overview of the current state of manufacturing techniques for metamaterials and addresses key challenges and opportunities for scaling-up production and advancing commercialisation. The roadmap is structured around three metamaterial categories, mechanical, electromagnetic, and acoustic metamaterials, with each spanning additive, subtractive and formative manufacturing approaches. This structure reflects the context-dependent nature of metamaterial manufacturability, where manufacturing requirements vary significantly according to the operating physics, characteristic length scale, material system, production volume, and application domain. Each section follows a common framework addressing the current state of manufacturing, key challenges, and emerging scientific and technological advances required to overcome these barriers. This roadmap highlights the manufacturing pathways required to bridge the gap between emerging metamaterial concepts and their practical implementation at industrially relevant scales.



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Figure 2. Annual publication counts for mechanical, electromagnetic, and acoustic metamaterials from 2014 – 2025, derived using Google Scholar. Searches were performed using phrase-based queries ("mechanical metamaterial", "electromagnetic metamaterial", "acoustic metamaterial"; each combined with its plural form). For additive manufacturing (AM), each metamaterial query was further combined with the Boolean filter ("additive manufacturing" OR "3D printing" OR "3-D printing" OR "additively manufactured").

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2. Additive manufacturing of mechanical metamaterials

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Status

It is not a coincidence that the recent explosion in mechanical metamaterials (MM) research followed the rapid developments in additive manufacturing (AM) [1]. MM typically derive their exotic properties from complex geometry at the local scale and AM offers unique geometrical flexibility, unmatched by conventional manufacturing processes. MM properties include behaviour which is unusual, or even impossible, in homogeneous materials typically used in consumer and engineering products. Examples include a negative Poisson's ratio, high energy absorption capability, multistability, vanishing shear modulus and more [2]. Many types of MM are observed in biological systems, such as bone, which often provide inspiration for engineered counterparts. Other types of MM are found in everyday applications, albeit known by other names (e.g. corrugated sheets, honeycombs and foams). The AM process, as a route to produce MM products, represents a large domain of processes with a diverse range of energy requirements, resolutions, output scales, technological maturity, and feedstocks (filament, powder and liquid are all commonplace). Their primary common characteristic is the local deposition of material with very little material waste. They can be contrasted with subtractive processes that produce geometry by removing mass from the workpiece and transformative processes that change the shape of the workpiece without adding or removing mass. Commercial adoption so far mostly lies at the two extremes of product sophistication – rapid prototyping and high-value applications.

The advantages of AM processes in the MM context extend beyond geometrical flexibility and net-shape production. They are inherently digital processes ideally suited to the analytical definitions of many MM designs. They require minimal lead time, since no additional tooling or fixtures are needed. Less capable versions of processes, such as low-cost desktop polymer AM machines, are now ubiquitous. AM processes work with diverse material systems – including soft materials and composites. In addition, in-situ material creation and multimaterial systems are also possible, while hybrid AM/machining platforms are available for certain materials. Large communities of researchers and enthusiasts are also active and help accelerate AM progress.

The bulk of recent developments in MM have relied on polymer AM processes for proof-of-concept and initial exploration. Polymers have been at the forefront since the majority of work on MM focuses on elastic properties which are more easily examined with compliant materials. Polymer AM is also significantly cheaper than metal AM. The adoption of AM for mass production and, therefore, the potential of AM to be a viable route for introducing MM in consumer products remains limited, as outlined in figure 1.

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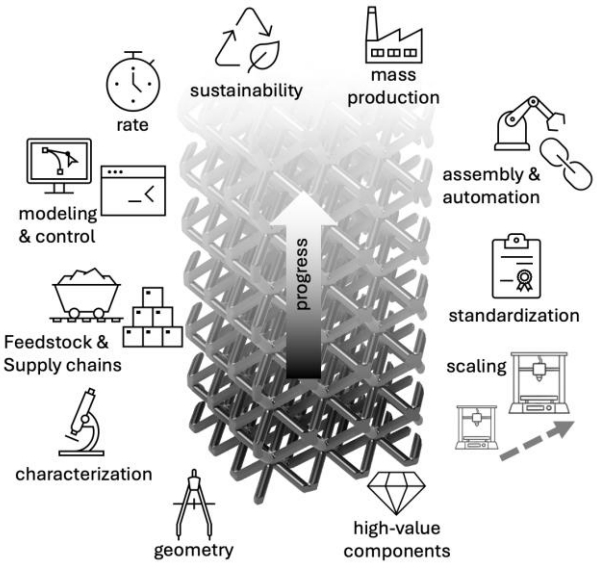


Figure 1. An illustration of capabilities and challenges for additive manufacturing of mechanical metamaterials given in a relative order of maturity. i.e. Complex geometries are easily feasible, but mass production capabilities are still an aspiration for most applications.

Current and Future Challenges

AM is primarily hindered by the slow rate of production, post-processing requirements and the high relative cost compared to other manufacturing routes [3]. Typical centimetre-scale components can require hours to produce with AM while forming and injection moulding processes can output parts in seconds. To prevent additively manufactured MM components from becoming bottlenecks in complex product assemblies, workflows and production rates need to match other production processes.

At the same time, the sustainability of AM processes is usually low for large batches, since the material is typically sintered or melted before deposition. However, for small batches, AM can be at an advantage because of the environmental cost of dedicated dies in forming processes [4]. This balance is process- and geometry-dependent: a cradle-to-gate LCA of a laser powder-bed-fused lattice automotive component found that despite a mass saving, the longer build time reduced productivity and increased energy use enough to outweigh the environmental benefit relative to an equivalent solid design [5]. Nevertheless, sustainability increasingly is a core product requirement.

AM processes have substantial dimensional limitations, both on the overall size of products and on resolution, with pronounced trade-offs between these and production rate. Many envisioned applications for MM are aimed at the automotive, aerospace, marine or construction industries; as a result, routes to achieving production at corresponding dimensional scales are therefore needed. For safety-critical products in those industries, the novelty of many AM processes and feedstocks adds certification challenges [6]. Similar complications exist for biomedical applications and implants, although these applications may benefit from the ability to customise/tailor specific designs. The Adidas 4DFWD running shoes with an impact-absorbing mid-sole is an early consumer-grade example [7]. At micro- and nano-scales, AM introduces new opportunities but also additional fabrication hurdles, e.g. relating to the diffraction limits of photopolymerization-based processes or the thermal gradients in powder-bed fusion, both of which restrict the minimum achievable strut diameter and nodal connectivity. At these scales, AM allows for exploration of scaling and geometrical hierarchy effects, with multifunctional applications [8].

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The quality and availability of suitable AM materials is an important consideration for future developments and commercialisation of MM. Feedstocks therefore need to be standardized and diversified. Quality feedstock – for example, by sieving to remove debris and oversized particles, and by drying to prevent agglomeration – helps eliminate defects and variability in products, which can be particularly detrimental to the precision features required in many MM [9]. The ability to predict and avoid common AM flaws is another ongoing challenge that impacts MMs (e.g. residual stresses, porosity, anisotropy). A major challenge is developing MM designs and applications beyond the linear elastic regime. Nonlinear constituent material domains such as viscoelasticity, fracture and plasticity can offer new frontiers of exploration, but they need to be considered alongside enabling AM technologies. For example, metal MM designs for shock absorption force a consideration for material behaviour during plastic deformation and constrain the range of suitable AM processes [10]. In general, MM production using metal AM represents a prominent gap and a significant opportunity given the higher performance demands and value density of metal components in infrastructure applications.

Advances in Science and Technology to Meet Challenges

Increasing the output rate of AM processes remains an ongoing challenge. Energy-rate limits for AM impose practical throughput ceilings compared with high-volume forming/moulding [3], reinforcing that cost competitiveness hinges on lot size, customization value, and post-processing load. An alternative approach is to scale in terms of the number of machines in production facilities and to reduce preparation and post-processing requirements. The latter demand better process modelling and control e.g. to compensate for residual stresses, anisotropy and porosity. Dimensional scaling does not have these inherent ceilings, except for certain metal AM processes which require a controlled environment. For centimetre scale unit cells of MM, conventional manufacturing and assembly become more attractive. When unit cells are only feasible through AM, scaling can be achieved with suitable assembly and joining technologies, including automated material handling, fasteners, adhesives and welding. The impact on MM behaviour therefore needs to be accounted for at design stage. Similarly, combining MM with other structures can offer new design possibilities such as controlled crack propagation at interfaces [11]. Further integration of AM with conventional manufacturing and hybrid production systems will accelerate such developments. The increased availability and sustainability of feedstocks is partly a function of demand. However, advanced technologies are needed to improve recyclability, such as improving uniformity and characterisation of feedstock powders [9]. Similarly, reduced post-processing can be achieved by improving the inherent surface finish and mechanical properties.

Technological innovations can go beyond production technologies to make AM of MM more appealing. Dedicated MM design tools employing implicit modelling for lattice geometries are already emerging, but higher standardisation of MM features would accelerate their adoption. Advanced software tools that incorporate AM process constraints in design workflows are also becoming available, but they must reliably link to MM properties. For example, some topological MM designs necessitate large variations of local stiffness across a lattice, close to the limit of many current AM technologies [14]. At the same time, AM of MM introduces trade-offs in mechanical properties which are scarcely examined holistically [15]; corresponding design approaches would be invaluable. Similarly, multifunctional metamaterials which combine mechanical properties with active materials can already be facilitated by AM but would accelerate if suitable design tools were common [13], enabling actuation, sensing, energy harvesting and more. Process regimes differ markedly in governing

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physics, resolution, throughput and feedstock (Table 1), which must be captured in design tools that map to target MM behaviours. Research is therefore needed to map feasible MM and candidate applications so that realistic measures relating to production environmental impact become available and LCA tools become more reliable and widely available. The ongoing work by standards committees such as ISO/TC 261 and ASTM F42 will be indispensable to all the above.

Table 1. Comparative summary of primary AM routes for mechanical metamaterials.

Process	Governing physics	Resolution	Throughput / scale	Feedstock	Post-processing
Two Photon Polymerization (TPP)	Optical diffraction limit; resin cure kinetics	sub-µm [8]	Low; voxel-by-voxel; mm-cm parts [3]	Photopolymer resins	Uncured resin removal
Stereolithography (SLA)	UV/laser photopolymerization, layer-wise curing	tens of µm	Moderate; mm-cm parts	Photopolymer resins	Uncured resin removal, UV post-cure
Powder Bed Fusion (PBF)	Melt-pool stability; thermal gradients (porosity, anisotropy)	tens of µm	Moderate; cm-m structural parts [12]	Polymer (e.g. nylon) or metal powders, e.g. Ti, steel alloys [9]	Powder removal, stress relief, substrate cutting [6]
Direct Ink Writing (DIW)	Rheology and inter-bead bonding	~100 µm–1 mm	Moderate-high; continuous extrusion; cm-m parts	Pastes/inks, elastomers, hydrogels [13]	Curing, cross-linking or drying

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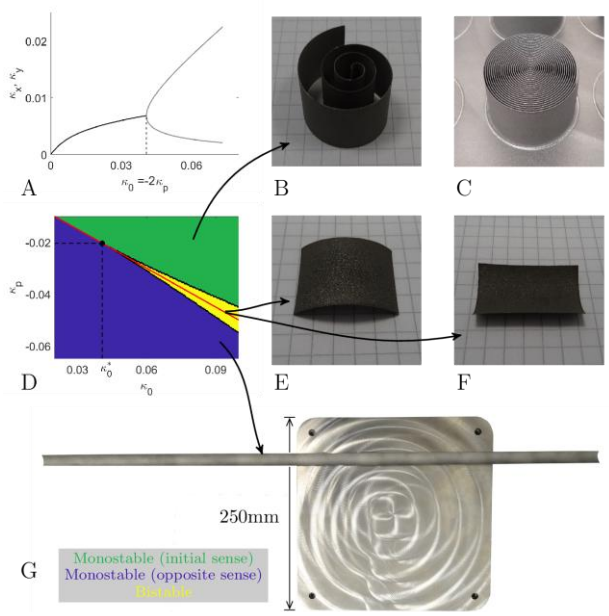


Figure 2. The synergy between AM and MM goes beyond complex geometry. Residual stresses and springback inherent in AM can enable nonlinear behaviour which in turn facilitates new product functionality and extends AM capabilities. A titanium spiral shell, printed on a Selective Laser Sintering machine demonstrates multistability. Adapted from [12].

Concluding Remarks

The nexus of AM and MM technologies represents an exciting domain that combines challenges and opportunities in production engineering and mechanics. AM already serves the MM field well, enabling rapid exploration of complex, tailored geometries and providing a feasible route for high-value applications—the medical domain is particularly attractive in this regard [16]. For this symbiotic relationship to flourish further, innovations are needed in feedstock quality, scaling strategies, and process modelling to mitigate defects and variability. In the near term, progress will come from process-aware design tools, clearer characterisation and qualification practices, and improved feedstock consistency. Over the medium term, assembly-based scaling, sector-appropriate sustainability assessment, and multifunctional hybrid architectures will expand the feasible design space and bring AM-enabled MM closer to robust industrial deployment. In the long term, advances in automation, inline control, and MM-aligned standards will be essential to unlock mass-production capabilities and realise the benefits of mature manufacturing routes. Ultimately, AM and MM should continue to be treated holistically: doing so will not only accelerate the transition from laboratory concepts to scalable products but also enable MM to feed back into AM itself—expanding AM capabilities (see [17] and figure 2 for examples) and delivering value across the wider Manufacturing sector [18].

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3. Subtractive manufacturing of mechanical metamaterials

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Status

Subtractive manufacturing methods represent the backbone of mass production techniques of industrial parts and machine components. Contrary to additive manufacturing (AM) methods, which are based on layer-by-layer addition of material, subtractive manufacturing (SM) techniques involve the gradual removal of material from a full block to eventually achieve a desired form. In the field of mechanical metamaterial (MM) manufacturing, AM has long since been the most widely used fabrication method due to its ability to realise intricate, complex 3D geometries with an extremely wide selection of permissible constituent materials and relatively simple setup procedures at the preprocessing stage. However, despite the obvious advantages of AM, SM methods should not be discarded since they still present a viable route towards the manufacturing of MMs and in some cases represent the superior option in terms of final resolution, quality and fabrication speed.

SM technology is primarily well-suited for the design of perforated auxetic mechanical metamaterials (shown in figure 1). As their name implies, this class of negative Poisson's ratio systems are formed by the introduction of patterned perforations in a block or sheet of material [1-3]. Many of these designs are also known as "kirigami" auxetics [4,5] after the ancient Japanese art of folded paper cutting from which several auxetic patterns are inspired. These metamaterials, which have the ability to exhibit an extremely wide spectrum of Poisson's ratios ranging from giant negative to highly positive values, are mainly 2D systems which can easily be produced through SM methods such as laser-cutting or computer numerical control (CNC) milling. The amount of material which must be removed is typically minimal, with many forms involving simply the introduction of cuts/slits, while others require the cutting of small patterned holes which usually amount to less than 20% of the original surface area. Furthermore, many of these mechanical metamaterials also have the advantage of being functional with nominal extruded depth, meaning that they can be cut/milled from thin sheets of material rather than requiring thick blocks with large out-of-plane thickness. These factors allow for the production of perforated metamaterials to be carried out at an extremely fast rate using SM in comparison to AM methods and, particularly for slit-perforated systems, with considerably improved quality since in typical low-end vat photopolymerization and fused-deposition AM devices the fabrication of small pores/channels is problematic.

In this section of this roadmap, the current SM methods used to produce MMs will be discussed along with their advantages and disadvantages. Future applications and challenges involving the SM of MMs will also be covered.

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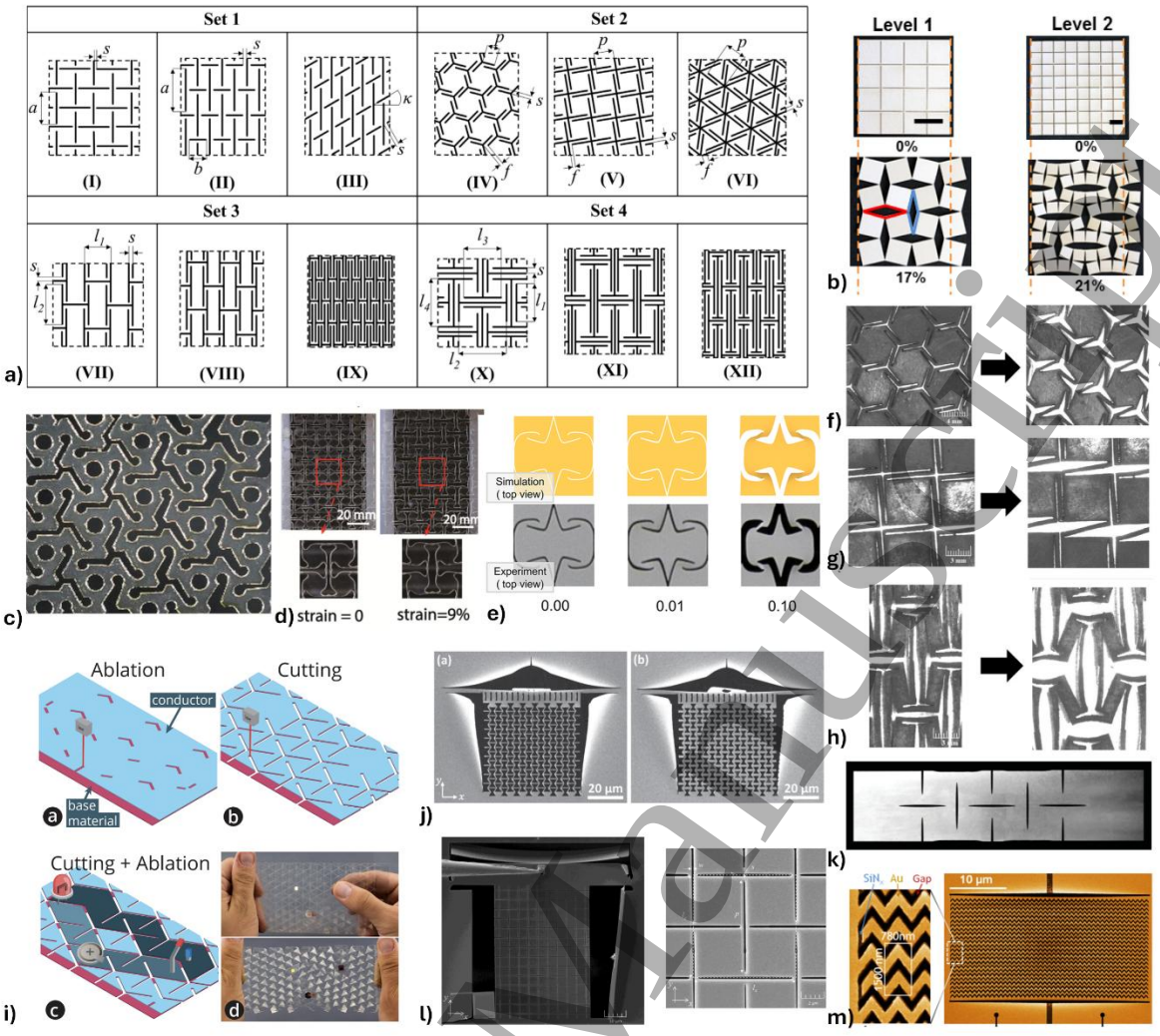


Figure 1. a) Designs for patterned slit-perforated auxetic metamaterials [6], b) hierarchical rotating square metamaterials produced through laser-cut slits [5], c) laser-cut hydrogel [7], d) acrylic [8]and c) PET auxetic metamaterials [9]. Panels f), g) and h) show rubber laser-cut metamaterials [6], i) laser-cut auxetic circuits [18] and while k) [11] shows CNC fabricated metallic MMs. Finally, j) [12], l) [13] and m) [14] show reconfigurable MMs produced through FIB-milling with nanoscale geometric features.

Current and Future Challenges

The fabrication of MMs through SM methods can be broadly divided into three groups: CNC machining, Laser Cutting and Focused-Ion Beam (FIB) milling.

1) CNC machining is the SM method which is most widely used in industrial settings and involves the use of drills, mills and grinders removing material mechanically through a preprogrammed pathway from a full block or sheet. It is primarily well-suited for the cutting of metals, wood and “hard” polymers such as Nylon and PEEK. It is not commonly used for the fabrication of MMs since most commercially available devices can only be used to produce macroscale architectures with a high degree of precision. In addition, the restricted number of permissible constituent materials is also a considerable limiting factor as metallic MMs typically have a low strain tolerance capacity and thus additional design considerations must be taken into account, such as additional filleting at the high localised stress regions [10-11], to improve the stretchability of CNC-manufactured systems. Despite these limitations, this technology has potential to be utilised for the large-scale fabrication of metallic metamaterial sheets since

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corresponding AM methods such as powder-bed fusion are extremely costly, time consuming, generate significant material waste and produce an overall mechanically inferior end-product.

2) Laser-cutting of MMs is more widely employed. This technique can be utilised on a much wider range of material classes than CNC milling and includes metals, plastics, elastomers, ceramics and organic materials. Typically, a CO_2 laser is used with the potency depending on the material being cut and the thickness. Laser-cutting can also achieve micro-scale level precision and is relatively fast – thin samples can be cut with a single pass run in a matter of minutes. These factors make this SM technique ideal for the design of complex slit-perforated 2D MMs since they can be rapidly produced with high accuracy [5], [8-9]. The suitability of this method for cutting elastomers such as silicone rubber [6] and hydrogels [7] also sets it apart from other SM techniques since it allows for its use in the production of highly stretchable auxetic systems. In the case of these materials, a minimal post-processing step is normally required involving cleaning through sonication of the sample after cutting. The accuracy of laser-cutting depends primarily on the thickness and type of material used, with thinner sheets yielding the highest resolution of cutting.

3) FIB-milling involves the use of a heavy ion beam, typically Ga^+, to bombard a surface resulting in structural modifications such as milling, etching and sputtering. This method exhibits extremely high resolution and is well suited for the design of architectures with lower micro- or nanoscale geometric features. Given the small scale of the cuts, cost of the device and relatively large amount of time required for milling, this method is unsuitable for large-scale metamaterials and is used only to produce small sheets of plasmonic metamaterials with global dimensions below 1 mm and local geometric features with parameters as low as 200 nm. Recently, it has also been utilised to produce micro-/nanoscale auxetic MMs with relatively large deformation capacity, highlighting its potential to be used as a fabrication method for reconfigurable plasmonic MMs [12-14]. This method can only be used to mill conductive materials such as metals and gold-coated semi-conductive ceramics such as Silicon Nitride. Attention must also be paid to the influence of nano-manufacturing factors such as internal residual stresses [15] of the base material when planning the manufacturing pathway, since they could lead to failure of the fabrication process.

These three methods encompass SM for MMs at the macro-, micro- and higher nano-level and use widely differing technologies, yet they all suffer from one identical major limitation – they cannot be used to mill complex 3D architectures. This restriction, which arises from practical considerations relating to the inability of the SM device to reach internal regions of the block to remove material, makes it impossible for SM techniques to be used to realise geometries with internal pores or deep channels, hence limiting the applicability of these methods to the design of 2D MMs.

Advances in Science and Technology to Meet Challenges

The dimensionality limitation for SM is fundamentally insurmountable at current technology levels. While some complex 3D MMs with a small number of representative unit cells containing externally accessible pores can in theory be realised utilising an expensive 5 or 6-axis SM device following a painstakingly difficult and laborious design process, AM still presents a much easier and cheaper route towards the manufacture of these systems. Furthermore, architectures with small internal pores or

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externally inaccessible hollow structures cannot be realised by SM. Given the eminent suitability of alternative methods such as AM for 3D systems, recent advances in SM of MMs have focused more on optimising the precision and accuracy for the manufacturing of 2D architectures and extending the scalability towards the nano-level.

For these systems, the fabrication speed of SM techniques by far exceeds that of AM. In the past, this advantage was offset by the complicated, time-consuming machine pathway pre-processing step but nowadays modern milling machines are capable of calculating this autonomously from a simple image file and fabricating the system without reorienting the initial piece of material for 2D systems, similar to how AM devices automatically compute the building from a CAD model. SM also has the major advantage in that it does not change the structure of the internal constituent material, unlike AM which typically imparts anisotropy as a result of hierarchical tessellation-based fillings or, in the case of metallic prints, elongated grains and presence of internal defects. Through smart design of 2D MMs, one can optimise the geometry for ease of manufacture with SM methods. In fact, the field of perforated/kirigami metamaterials is primarily aimed at exploiting the advantages of SM techniques for the efficient fabrication of auxetic metamaterial sheets. The vast majority of this class of MMs comprise of architectures which involve only the introduction of slits [3-4], [16] or small area cuts [17]; thus removing only a minute amount of material; allowing for quick realisation of 2D metamaterials without significant material waste – therefore eliminating another potential drawback of SM which is frequently mentioned. These factors give SM a definitive edge over AM for the manufacture of low-porosity 2D mechanical metamaterials, in particular thin metamaterial sheets, since they can be fabricated much faster and cheaper whilst ensuring minimal material waste.

SM of 2D MMs presents a number of opportunities for the manufacture of sheet-like mechanical metamaterials which could be implemented in various settings such as wearable, stretchable devices [18], shape morphing surfaces [19] or even skin-grafts [2], as well as soft robotic morphing systems which can evolve from 2D sheets to complex 3D architectures [20]. In addition, SM can also be used for the fabrication of tubular auxetic systems through the use of a 4-axis device similar to the manner in which coronary stents (which can also be considered as MMs in their own right) are currently mass-produced on the industrial level [21]. The utilization of recently developed AM devices which incorporate a CNC milling or laser-cutting component could also be a potential future hybrid solution which may overcome the dimensionality limitation of standard SM methods. One example of this hybrid method is the incorporation of femtosecond laser ablation technology with two photon polymerization to produce microscale wave-guide metamaterials [22]. Further down the road, the novel field of reconfigurable plasmonic MMs also offers many exciting prospects. Currently, FIB-milling is capable of achieving levels of resolution which significantly exceed those afforded by the most advanced stereolithographic AM methods and the incorporation of MMs in plasmonic metamaterials is envisaged to lead to significant advances in the near future. Many practical aspects still remain to be solved such as how to stimulate the actuation necessary for reconfiguration and control of residual stress-induced deformations, however SM methods still lead the way in this breakthrough area of metamaterial research.

Concluding Remarks

Subtractive manufacturing techniques offer a viable cheap and quick alternative to additive manufacturing for the design of 2D mechanical metamaterials. Besides the mass production of these metamaterials, it can also be utilised for the fabrication of tubular auxetic systems such as biomedical implants as well as for the production of plasmonic reconfigurable mechanical metamaterials with

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nanoscale geometric features and other lower microscale metamaterial architectures due to the high resolution of methods such as FIB-milling.

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4. Formative manufacturing of mechanical metamaterials

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Status

Mechanical metamaterials are engineered structures, with combinations of effective mechanical properties that cannot be achieved from the unstructured, intrinsic constituent materials they are made from. This section spans various forms and applications of mechanical metamaterials, focussing on the potential for formative manufacturing approaches to benefit scaled production. The formative manufacturing of mechanical metamaterials includes moulding, extrusion and shaping processes to impart such structures. These have been applied to mechanical metamaterial types that range from auxetic polymer fibres and films to kirigami/origami sheets, and various lattices, foams, and honeycombs.

The field now known as mechanical metamaterials research began, in earnest, in the 1980s, when Rod Lakes made auxetic (negative Poisson's ratio) foam using a formative (heat and compression moulding) process to modify the cell structure of thermos-plastic polyurethane foams [1]. Engineered structures with mechanical properties beyond their intrinsic constituents appeared before this. The graphite cores of Magnox nuclear reactors, first installed in the UK in the 1950s, were made from moulded, interlocked sections that produce effective negative Poisson's ratio [2].

Mechanical metamaterials research has benefited from new (typically additive) manufacturing capabilities that allow precise definition of structures at small length-scales. Established structural optimisation processes, such as topology optimisation and generative design, can define effective material properties for required applications. While much of the recent research focusses on idealised, additively manufactured metamaterials (see Section 2), formative manufacturing of mechanical metamaterials aligns more closely to industrial processes, which allow cost-efficient mass production of parts.

While cost varies with part complexity and material choice, the cost of additively manufactured parts is typically lower than traditional approaches for a small batch size, as no tooling is required. This lower small-batch cost is then usually surpassed by that of traditional (e.g., formative) methods as batch size increases [3] – when the faster throughput of formative methods outweighs tooling costs. This change has broad variation, anywhere between ~50 to 90,000 runs [3], with lower than 10,000 runs typically being seen as a small batch size. An example of this in operation is seen within Rheon Labs moulding processes, that are used to mass-produce mechanical metamaterials for consumer products [4]

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Auxetic foam is one form of mechanical metamaterial that is usually made by moulding. Since its original fabrication, developments have focussed on improving consistency between fabrications, and applying new softening/fixing methods, e.g. using chemicals [4]. The foam materials used includes polymers (usually thermoplastic, including polyurethane, polyester, polyethylene, polyvinyl chloride, polymethacrylimide, and elastomeric silicone), and metals (typically copper) [4]. Co-polymers or additives included in such foams can affect the foam's mechanical properties, or the foam softening/fixing mechanism after moulding [5]. Fabrication methods are available for both open and closed-cell foams [4]. Various attempts have been made to align auxetic foam manufacture processes to those already used by industry [4]. Recent developments, typically using polymers, look to foam directly to an auxetic structure [6].

Extruded auxetic microporous polymers were first produced as cylindrical monoliths using a batch thermal processing method comprising compaction of thermoformable polymer powder, followed by sintering of the compact and, finally, extrusion of the sintered rod [7]. Centimetre-sized auxetic cylinders of ultra-high molecular-weight polyethylene [7], polypropylene (PP) [8] and nylon [9] have been made using the batch process. Subsequently, a continuous extrusion process using a conventional laboratory (25.4mm screw diameter) melt extruder was developed to produce auxetic PP [10], nylon and polyester monofilament fibres, and PP films [11]. The process has been successfully scaled to produce auxetic PP fibres on commercial (50mm screw diameter) extrusion facilities [12]. The successful production of extruded auxetic polymer fibres having diameters ranging from 0.2 to 2mm at production rates typically in the range 2-60 m/min has enabled demonstration of beneficial properties. These beneficial properties include enhanced indentation resistance, ultrasonic attenuation, and fibre pull-out resistance, leading to the development of innovative concepts for applications as diverse as smart wound healing bandages [13] and lightweighting in composites [14].

Moulding is also being used to mass produce idealised structures, such as honeycombs [15]. Such moulding (or casting) can be applied to a broad range of materials (e.g., polymers, metals, and ceramics), and relationships between geometries that can be moulded, and material properties are well understood. Microscale moulding with variation in three orthogonal axis is inherently challenging, with mould cost and sample extraction being limiting factors. None-the-less, viscoelastic polymers that can be slowly extracted from a mould (and remain soft) are seeing mass production in sports products [16]. Moulded sections have also been assembled to form lattice mechanical metamaterials [17], a process which shows potential for streamlining toward larger scale production.

Sheet forming methods such as origami – the ancient art of paper folding – have contributed to enriching the scope and design space of metamaterial structures over the past few decades. Such metamaterials are generally developed based on well-known origami tessellations such as the Miura-Ori [18].

Current and Future Challenges

The major challenges for widespread realisation of the potential of mechanical metamaterials form a trade-off, between manufacturing cost, structural complexity, and the degree of control over imparted structures [19]. The field has seen rapid expansion, often focussed on achieving extreme properties, or combinations of properties. After modifications to align production costs with consumer demands, and to maintain production consistency, available properties are often less close to their physical limits [19]. These modifications, often driven by production cost, may include limits to achievable features sizes (e.g., cell, grain, etc.), or reducing the number of axes which the metamaterial varies in (e.g., selecting honeycombs over lattices). The various formative processes already applied to mechanical

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metamaterials share combined challenges related to process selection, and distinct technical challenges.

Mechanical metamaterial design processes typically have two strategies [19]; i) those starting with a manufacturing process, guided by know-how, or optimisation that is constrained to certain dimensions and variation in a pre-defined number of axes; ii) those started with selection of a geometry to give an optimal function, that is later adapted to suit a fabrication or manufacturing process. While function is clearly important, cost-benefit trade-offs (and indeed sustainability measures) are the key commercial principle. Yet, while some prior work has been done on these topics [3,20], there remains a lack of digital tools that couple predictions of manufacturing costs, economic and sustainability life cycles analysis, and function within optimisation objectives. During laboratory-scale analysis, while the lower mass of metamaterials parts reduced raw material requirements, additional energy input needed to make them still outweighed these benefits [20]. These limitations may explain some of the challenges realising commercial application of mechanical metamaterials.

While “one-pot” auxetic foam moulding methods may simplify and reduce cost in auxetic foam manufacture, the degrees of freedom to impart useful gradient structures, or extreme degrees of anisotropy, have not been shown using these methods. The auxetic foam manufacturing process also remains variable at the microscale; the shape of a cell is not defined, but processing conditions are selected to produce an average cell shape and set of mechanical properties [21]. Such local variation can be advantageous, as it reduces the likelihood of shear failure bands observed in periodic structures. Nonetheless, this manufacturing process does not align to microstructural optimisation. Further work could study relationships between cell formation and processing conditions, to provide more control over foam microstructures. Moulding processes for idealised structures, and those combining moulding and assembly, have seen less academic interest than auxetic foam manufacturing, despite evidence that they are commercially viable [16].

Challenges associated with the extrusion of auxetic polymer monofilaments include achieving uniform properties along the fibre length, reducing the fibre diameter below ~100 µm (required for most apparel applications and the lightweighting in composites concept, for example), and achieving production throughputs comparable with those achieved for commercial production of conventional monofilaments (typically 1000-2000 m/min). In the laboratory-scale fibre extrusions these are all a consequence of the process relying on the partial/surface melting (as opposed to complete melting in conventional monofilament extrusion) of polymer powder particles to create the fused particle microstructure responsible for the auxetic effect [11[. Very close control is required over processing parameters where, for example, the laboratory-scale extrusion temperature for auxetic PP fibres is within a narrow window (between 157 and 163°C) [22].

Origami- and kirigami-based metamaterials have attracted a great deal of attention in recent decades. The manufacturing processes of kirigami-based metamaterials in macro-scales are often straightforward, as their fabrication is dominated by precision cutting of 2D materials, a task that is easily performed by modern laser or blade cutting machines. On the other hand, while a wide range of geometric/mechanical design and numerical analysis tools have been introduced to support the design of origami structures, the manufacturing process of many folded structures has remained a challenge. More specifically, a key property of deformable origami structures is the integrity and durability of their fold lines. Polypropylene and polyethylene, which form ‘living hinges’ that can be repeatedly folded/unfolded without breaking, have been considered as almost ideal materials for the seamless manufacturing of polymeric origami structures with integrated living hinges. Other substrates such as polyether ether ketone, and fibre-polymer composite (Kevlar, PEEK, carbon-fibre,

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and polypropylene with embedded flax) have also been used to make relatively large-scale Kirigami metamaterials [23].

Commonly, modern origami artists and practitioners make scored or perforated crease patterns using blade or laser cutting machines, followed by folding the outputted flat sheets to form the intended 2D or 3D geometries [24]. Such manual fabrication processes are, however, generally time-consuming, and require a high level of skill and precision, and automation may have benefits. Kirigami is an example of a hybrid manufacturing method – combining substrative methods with formative ones to improve design affordances.

On the other hand, one may think that commercially available additive manufacturing technology can address these manufacturing issues, but there are still major challenges in this regard. Importantly, despite groundbreaking advances in the additive manufacturing of various polymeric materials, the 3D printing of popular thermoplastics such as polypropylene and polyethylene is an existing challenge due to their low melting temperature and warping. As a result, commercial fused deposition modelling (FDM) 3D printers are frequently unable to directly produce origami structures out of such thermoplastics.

Advances in Science and Technology to Meet Challenges

To align optimisation regimes for mechanical metamaterials to industry requirements of cost/benefit trade-offs, there is a fundamental need for cost and sensitivity predictors to be included in objective functions. Recent trends in digital manufacturing, whereby quality, cost, scrappage rates, and tool/mould degradation are tracked and stored [18], would form useful starting points for such digital tools. Such development may require substantial effort and involvement between industry, academia, and developers/providers of structural optimisation tools. The trade-off between cost, sustainability and benefit, and lack of interface to calculate both, is not limited to mechanical metamaterials. Previous substantial initiatives in artificial intelligence (AI) driven bulk material design have benefited global economies; the Materials Genome, that cross-cuts the US materials landscape, estimates economic benefits above $100 billion per year [26]. As such, a range of design exploration tools are available, that could be adapted to improve the design of mechanical metamaterials. For example, integrating non-physical attributes into microstructural optimisation may benefit from the use of AI tools to combine complex data sources, allowing prediction and tracking of economic, environmental, and supply chain security metrics.

Concerning auxetic foam manufacture, and formative processes to impart locally variable foam-like cell structures, these have potential to be cost-efficient processes that can achieve extreme mechanical properties across relatively small length scales. In a similar approach to the Malta University spin-out Smart Materials Ltd, investment in experimental processing plants with comparable facilities to large foam production plants would further development of scalable methods to impart extreme mechanical properties. Such processes could widen access to one-pot auxetic foam production, or widen process options by producing (for example) tailored anisotropy, or gradience of mechanical properties [21].

To achieve uniform and finer extruded auxetic monofilaments at commercially viable production rates will require molecularly engineered auxetic polymers to enable the auxetic effect at the polymer chain level through extrusion of fully molten polymer. Here the recent reports of auxetic liquid crystalline elastomers (LCEs) [27] offers promise and an avenue for research into fibre-forming auxetic LCEs. Alternatively, identification of mechanisms for auxetic behaviour at polymer chain level in naturally-occurring auxetic polymers, such as crystalline cellulose [28], should enable fibre-forming

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synthetic equivalents, possibly facilitated by high throughput techniques and AI and machine learning approaches. The production of auxetic PP monofilaments on a commercial extruder, and also PP films on a laboratory-scale extruder, have been reported at higher extruder temperatures (180-200°C, where the polymer is fully molten during processing) [12,29] than the laboratory-scale extruded fibres. This indicates that polymer chain-level auxetic mechanism may operate in the higher temperature extrudates.

Moulding mechanical metamaterials with microstructural variation in three orthogonal axes is relatively unexplored but has substantial potential to increase manufacturing options. It is well known that soft materials can be removed from moulds that contain overhangs, although these are often too soft for engineering applications. The process adopted by Rheon labs [16]; moulding viscoelastic polymers that can be slowly removed from moulds with overhangs but stiffen under impact (i.e., in application) is promising. Unexplored options include two-stage processes, whereby soft polymers are cured, treated, or coated, after moulding, to increase their stiffness. Similarly, hybrid processes such as moulding and assembly, or subtraction, may increase degrees of freedom during scalable manufacturing. Automation of such processes, using Industry 4.0 technologies to create smart, connected, and automated processes have potential to streamline such hybrid methods.

Concerning origami-based metamaterials, recent advances in the additive manufacturing of durable and fatigue-resistant thermoplastic polymers such as polypropylene have been opening new horizons for the manufacturing of such metamaterials [30]. However, currently, many commercial 3D printers are not designed to take filaments such as polypropylene and polyethylene as input materials, and those with such a capability remain a niche on the market of 3D printers. On the other hand, adaptions to laser-scoring/perforating followed by manual folding, such as robotic folding [31], have automated the manual process. Honeycombs can also be efficiently produced by kirigami-like methods of continuous cutting, folding and gluing [32]. There remains little evidence that robots can replicate the manual, skill-demanding folding process for complex, intricate origami structures based on scored or perforated sheets of materials; such capabilities should be tested and developed.

Concluding Remarks

With the holistic prototyping capabilities of additive manufacturing, formative processes to manufacture mechanical metamaterials are less frequently applied in published literature. Origami or kirigami structures, auxetic foam, extruded polymeric auxetic fibres and filaments, and advanced moulding processes are exceptions to these trends, but often remain challenging at scale. Further work developing these processes, and hybrid approaches (i.e. combining subtractive or additive approaches with formative ones), may help reduce large-batch manufacturing costs for mechanical metamaterials, improving commercial viability. While there is clear benefit to developing these manufacturing methods, it is also important to also develop modelling capabilities (to include manufacturing costs), and target applications supported by empirically evidenced benefits. With availability of options to scale manufacturing processes, and efficiently design cost-effective metamaterials, as well as strong evidence to show benefits, the remaining manufacturing challenges are more likely to be solved organically.

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5. Electromagnetic metamaterials using additive manufacturing techniques

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Status

Radio frequency (RF) metamaterials are popularly used to manipulate electromagnetic (EM) wave properties [1], [2] with the aim to develop several new electromagnetic (EM) devices such as antennas [3], [4], absorbers [5], lenses [6], [7], reflectors [8], cloaking devices [9], and reconfigurable intelligent surfaces [10], [11]. Such systems are popularly shown to be used for advancing the field of wireless communications, radar, and sensing.

State-of-the-art literature contains numerous planar metasurface designs involving metallized components to achieve the above-mentioned devices using standard printed circuit board (PCB) fabrication techniques such as etching and machining [12], [13]. The introduction of additive manufacturing has added an extra degree of freedom for physicists and RF engineers to realize new complex 3D structures that enable bespoke material properties [14]. With a controlled grading of the material, one can vary the local relative permittivity [15], [16]. This ability to realize a varying relative permittivity with grading can be achieved in either one, two or three dimensions using additive manufacturing (see figure 1); and has enabled researchers to develop new isotropic and anisotropic solutions for different EM problems with high efficiency that are light weight and cost effective.

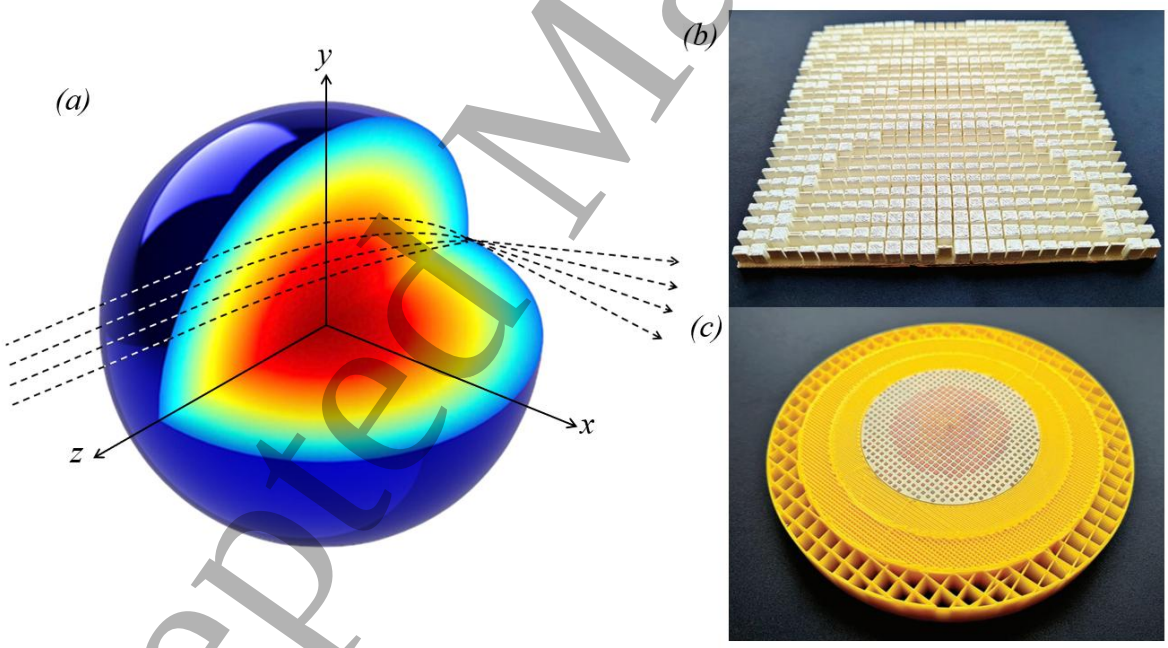


Figure 1. (a) A sketch of relative permittivity variation in three axes to manipulate EM beams; (b) an additively manufactured reflector metasurface varying the local phase [14]; (c) an additively manufactured 2D lens to achieve beamforming [14].

Current and Future Challenges

Current challenges within EM metamaterials manufacturing using additive manufacturing can be classified into the following categories:

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A. Materials: printable polymers and composites can offer a wide range of relative permittivity with modest losses, but key challenges occur as we aim for extremely low loss, finely graded materials. Furthermore, as we layer the materials, they tend to introduce anisotropy at different frequency bands due to irregular patterns, moisture absorption, and temperature variation. This drastically affects repeatability for any RF equipment using additive manufacturing. Several new AM materials such as ceramic based polymers have recently been seen in the literature that brings the promise for better electromagnetic performance.
Furthermore, most EM structures such as metamaterials and metasurfaces are a mix of dielectric substrate with metallic resonators. Metallic components being an intrinsic component, AM techniques use low conductivity inks, pastes and composites compared to gold, silver and copper. As an example, several companies such as Panasonic have produced silver nanowire-based optically transparent conductive layers, however, they tend to have very low conductivity. Using low conductivity conductors increase losses, which would impact the performance of resonant metamaterials and reduce their efficiency. Resonant RF metamaterials require high conductivity metals and low loss dielectrics, and compromising on these values often negates the advantages that metamaterial designs can promise in simulations. Recent developments in 3D printing have enabled several classical metal and metal alloys such as copper, aluminium, stainless steel, nickel, gold and silver to be 3D printed in different shapes. Even though new approaches have been seen in the literature, there are still extensive limitations on co-printing of metal and dielectrics. 3D-printing techniques can introduce microscopic air pockets within the final structure which presents the issue of outgassing for high altitude systems and space-related applications.

B. Processes, post-processing and property assurance: while additive manufacturing has demonstrated large success within academic research and bespoke high value items within industry, it is not yet suitable for mass manufacturing, primarily because of its slow fabrication process. Several AM techniques have been demonstrated in the literature to create metamaterials, these include fused filament fabrication (FFF), vat polymerization, powder bed fusion (PBF), and direct ink writing. All these methods depend on layer-wise printing of a 3D shape; hence, one must compromise with the resolution (or quality) of the design for fast printing. It is still difficult for AM techniques to outperform conventional PCB etching methods in speed and accuracy.

Table 1: Dielectric characterization facilities at Loughborough University.

Method	Freq (GHz)	Min Size	Max Size	Accuracy
Split-Post Dielectric Resonator	1.1	L: 120 mm W: 120 mm	W: 165 mm H: 6.0 mm	High
	1.9	L: 55 mm W: 55 mm	W: 100 mm H: 3.1 mm	
	2.4	L: 55 mm W: 55 mm	W: 100 mm H: 3.1 mm	
	5	L: 30 mm W: 30 mm	W: 90 mm H: 1.95 mm	
	10	L: 22 mm W: 22 mm	W: 90 mm H: 0.6 mm	
Cylindrical Cavity	1 – 10 (Sample Size Dependent)	Dia: 6 mm H: 3 mm	Dia: 14.4 mm H: 7.2 mm	High
Waveguide and Nicholson Ross Weir	8.2 – 12.4	22.86 × 10.16 mm H < ~ 4 mm		Medium
	18 – 26.5	10.668 × 4.318 mm		

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		H < ~ 3mm	
Damaskos 600T (Fabry-Perot Open Resonator)	10 – 70 (at each harmonic)	L: 120 mm W: 120 mm H: < 5mm	High

A significant variability has been recognized in additively manufactured devices from different research groups. Commonly used materials such as polylactic acid (PLA) are vulnerable to humidity and temperature changes, which can significantly impact the electromagnetic properties of the final 3D shape. Furthermore, surface roughness of 3D-printed devices has a significant impact at higher frequencies (> 60 GHz).

Metamaterials are highly dependent on accurate material characterization to better understand how a complex 3D-printed shape is going to behave when illuminated with different radio frequencies. Several material characterisation techniques have been developed globally to understand the inherent material properties and exploit it for different use cases. As an example, Table 1 gives an overview of different material characterization capabilities at the Wireless Communications Research Group at Loughborough University. Several research groups have shown 3D printing capabilities to print materials with relative permittivity as high as 30 but they come with challenges such as high dielectric loss, and poor print quality (e.g., surface roughness), both of which are extremely crucial for EM applications.

Advances in Science and Technology to Meet Challenges

Non-resonant metamaterials also referred to as artificial dielectrics are widely used in dielectric lenses. RF metamaterials that include resonant metallic elements, as of now, is being explored extensively in research, but there are no/few key end-user products that have been released. However, RF metamaterials using additive manufacturing are envisioned to develop large end-user verticals in the field of telecommunications, automotives, aerospace, defence, medical devices, and consumer electronics.

Some of the popular applications of the technology include developing new beamforming antennas with beam-steering capabilities for terrestrial public wireless networks. Future 5G and 6G technologies aim to use higher frequency bands to achieve high data-rate communication links. However, they tend to have high atmospheric attenuation. Beamforming is the key to resolve this issue and make beams highly directional to achieve long-range communication [17]. Additively manufactured metamaterial systems such as lenses and programmable intelligent surfaces are not only capable of generating highly directional beams, but they can also be used to generate multi-beams and control their direction in real-time. This allows us to build a new smart infrastructure for the telecommunication industry, which in turn, can support several other applications such as connected and autonomous vehicles, eHealth, internet of things, augmented and virtual reality, etc.

Metamaterials are popular within the defence industry and seen to have important use-cases; their capability to generate bespoke material properties with negative permittivity and permeability allows us to develop new cloaking mechanisms; they can be used as super-scatterers [18] to achieve reduced radar cross-sections [19]; alternatively, they can also be used to improve radar performance and achieve super-resolution [20].

The metamaterials industry is focused on developing artificial composites to engineer bespoke electromagnetic properties and is envisioned to exceed £10B globally by 2030. Apart from end-user products, the field of additive manufacturing for metamaterials has the potential to support several scientific and defence-based use-cases. Metamaterials' ability to produce lightweight devices makes them highly suitable for the aerospace industry. Their bespoke material properties have advanced applications in medical and sports science. With the integration of new materials such as

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semiconductors, phase change materials, flexible, and optically or electrically simulated materials, several new reconfigurable and intelligent devices can be realized.

Additive manufacturing allows easy and cost-effective prototyping, but we are still far from using it for mass production of end-user products. This is because of several limitations that current state-of-the-art technology has, which includes printing time, limited resolution, unwanted airgaps, outgassing and difficultly of printing conductors in situ with dielectrics.

Concluding Remarks

Additive manufacturing for RF metamaterials is a rapidly growing research topic, and we have started seeing a slow transition from research to industrial applications. AM provides several versatile techniques to manufacture dielectric and conductive materials simultaneously, which allows us to develop complex 3D structures that can offer bespoke electromagnetic properties. They are highly suitable for inexpensive rapid prototyping, and are being explored for significant applications in telecommunications, defence, aerospace, medicine, sports, etc.

Besides being a highly attractive area of research, AM for electromagnetic metamaterials has yet to be employed in notable commercial products to several challenges which includes repeatability, impact of environmental parameters (humidity and temperature), printing speed, high conductivity printing, surface roughness, etc. One of the key enablers for AM in the field of EM metamaterials is highly accurate material characterisation including measuring the anisotropy for both metals as well as dielectrics and has seen to be growing topic of interest among RF engineers and physicists.

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6. Atomic layer deposition for electromagnetic metamaterial applications

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Status

Reliable and high-resolution nanofabrication is vital for advancing electromagnetic materials. At the atomic scale, precise control over film composition, conformality and uniformity is vital as we demand more performance from less material. As such, atomic layer deposition (ALD) is playing an ever-increasing role in advancing new material technologies, *i.e.*, metamaterials. ALD is a vapour phase technique in which ultrathin films can be precisely grown on surfaces [1,2]. By this method, surfaces are sequentially exposed to vapour and/or gas species (*i.e.,* precursors) which react with the surface in a self-limiting manner, thus enabling precise control over the layer thickness and chemical composition at the atomic scale. By repeatedly exposing the surface to sequential pulsing of separate precursors, a thin film (typically sub nm to 100 nm) can be grown. ALD is typically performed between 20–300 °C, either thermally or from plasma. In metal oxide deposition, thermal ALD typically employs deionised water or ozone as an oxidising precursor, whilst for plasma ALD, an oxygen plasma is utilised. Additionally, lower temperature thermal ALD processes incorporating Lewis base catalysts (e.g. silicon dioxide) can be achieved [3]. In general, a wider range of materials can be deposited via plasma enhanced ALD due to the reactivity of the plasma enabling a larger range of precursors to be used. Beyond metal oxides, ALD is also capable of producing metal films, metal nitrides and metal sulphides. Irrespective of the process, ALD is one of the most advanced deposition methods in the market, making it possible to produce ultra-thin films with exceptional quality. In contrast to 'line-of-sight' deposition techniques (*e.g.*, chemical vapour deposition and physical vapour deposition techniques), ALD is capable at growing uniform and conformal layers on complex structures such as 3D structures and porous materials to nanoscale feature dimensions (*e.g.*, nm diameter vias conformally coated to high aspect ratios) [4, 5]. ALD metamaterial fabrication has already been demonstrated at lab-scale, having used effectively to deposit plasmonic Ag metamaterials for sensing applications [6], nanolayered metal oxides for optical metamaterials [7] and ultrathin alumina mechanical metamaterials [8]. ALD can be used in conjunction with other manufacturing techniques to realise metamaterials, such as coating additively-manufactured materials to alter their optical properties [5], pre-coating additive manufacturing feedstocks [9], or combining with etching to form patterned metamaterials for mechanical [8] or electromagnetic applications such as THz modulation [10].

Current and Future Challenges

Whilst ALD can deposit a multitude of thin dielectric and metallic films, the process to achieve such layers can be quite slow. For example, at a deposition temperature of 200 °C and an O_2 plasma co-reactant, the growth rate of aluminium oxide on silicon is ~0.13 nm/cycle [11], whilst for titanium dioxide the growth rate can drop to ~0.05 nm/cycle [12]. Deposition of metals often requires access to either H_2 and/or plasma capabilities, which may not be available in all manufacturing settings [2]. Despite the many advantages of conventional ALD, slow growth rates currently limit the thickness of dielectric or metallic films which can be achieved without sacrificing throughput – a key consideration for large volume technologies such as those in the photovoltaic and integrated circuit/semiconductor industries.

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For metamaterials, it is also important to consider how the ALD coating will be performed, as the most suitable approach will vary based on substrate and scale. For example, 3D or porous structures that require conformal coatings will require both significant deposition time (*i.e.,* each process requiring more time to reach hidden surfaces) and require a deposition system that can house these structures *e.g.,* ***flow-type*** or ***batch ALD,*** otherwise referred to as temporal ALD [2, 12]. In contrast, the same systems would not be suitable for large area flexible materials requiring high throughput coatings of large area, nor for coating powders prior to an additive manufacturing process (e.g., 3D printing).

Another consideration when using ALD to deposit ultra-thin films is how substrate surface condition affects growth characteristics. Immediate ALD growth, which is the desired form of growth, is achieved on surfaces that are uniformly terminated by hydroxyl (-OH) groups (e.g. SiO_2 coated materials). By this mechanism, the growth rate does not change with ALD cycle number. In contrast, delayed growth, which is less desirable, begins in the form of island growth at isolated reactive sites on the surface. After consecutive ALD cycles, the islands slowly coalesce and form a continuous film after which normal growth will result [2]. In such cases, the area average growth rate changes as the islands grow, however once coalesced, the growth rate remains constant. In contrast, intentional termination of the ALD process prior to coalescence can result in spatially isolated islands with potential for metamaterial applications [6].

Advances in Science and Technology to Meet Challenges

ALD is a well-established technique already capable of high-volume manufacturing and proven at scale. Common ALD technologies include flow-type, batch, spatial, roll-to-roll and powder, each of which may be more suited to different metamaterial designs/applications. For 3D/porous structures requiring extended deposition time and a system capable of accommodating such structures, a suitable approach may be ***flow-type ALD or batch ALD,*** otherwise referred to as temporal ALD [2, 13]. Flow-type ALD (figure 1a) uses a furnace chamber in which purge gases and precursors flow, sequentially, over/across the sample surfaces. Sample temperature is established *via* heating elements within the chamber walls and substrate holder. Although flow-type ALD produces high quality and uniform coatings, the process is considered too slow for mass production purposes due to the sequential nature of filling and purging the chamber for a single sample (*e.g.*, deposition of 20 nm of Al_2O_3 can take ~1 hr per sample) [2,14]. ***Batch ALD*** (figure 1b) is similar in nature to flow-type ALD, although utilising much larger chambers which house multiple samples simultaneously – an approach compatible with large-scale manufacturing *c.f.* in the semiconductor industry which achieves throughputs of up to 4000 wafers/hr [13]. For large area flexible materials requiring high-throughput coatings, ***roll-to-roll*** or ***spatial ALD*** would be more suitable options [1, 2, 15]. Spatial ALD techniques also offer substantially higher deposition rates of up to 100 times. ***Spatial ALD*** (figure 1c) involves separating individual cycle steps spatially rather than temporally. In this case, either the reactor heads or the sample itself passes through different reaction zones to grow the desired film. By this method, very high deposition rates can be achieved, whilst still maintaining high film quality, with similar throughput to that achieved by batch ALD [1, 2, 16]. ***Roll-to-Roll ALD*** (figure 1d) is a spatial ALD variant specifically tailored to flexible substrates, where either the substrate moves over a rotating drum which houses spatially divided reactor heads, or the substrate is wrapped around a drum in close proximity to 'rocker' reactor heads [15, 17]. ***Powder ALD***, suitable for applying thin conformal coatings to powders [18], consists of a heated drum held under vacuum, that rotates the particles as the precursors and gases are delivered to/from the rotating drum, thus ensuring uniform coverage [18, 19]. Fluidised-bed reactors (figure 1e) allow hundreds of kilograms of powder materials to be processed in each batch.

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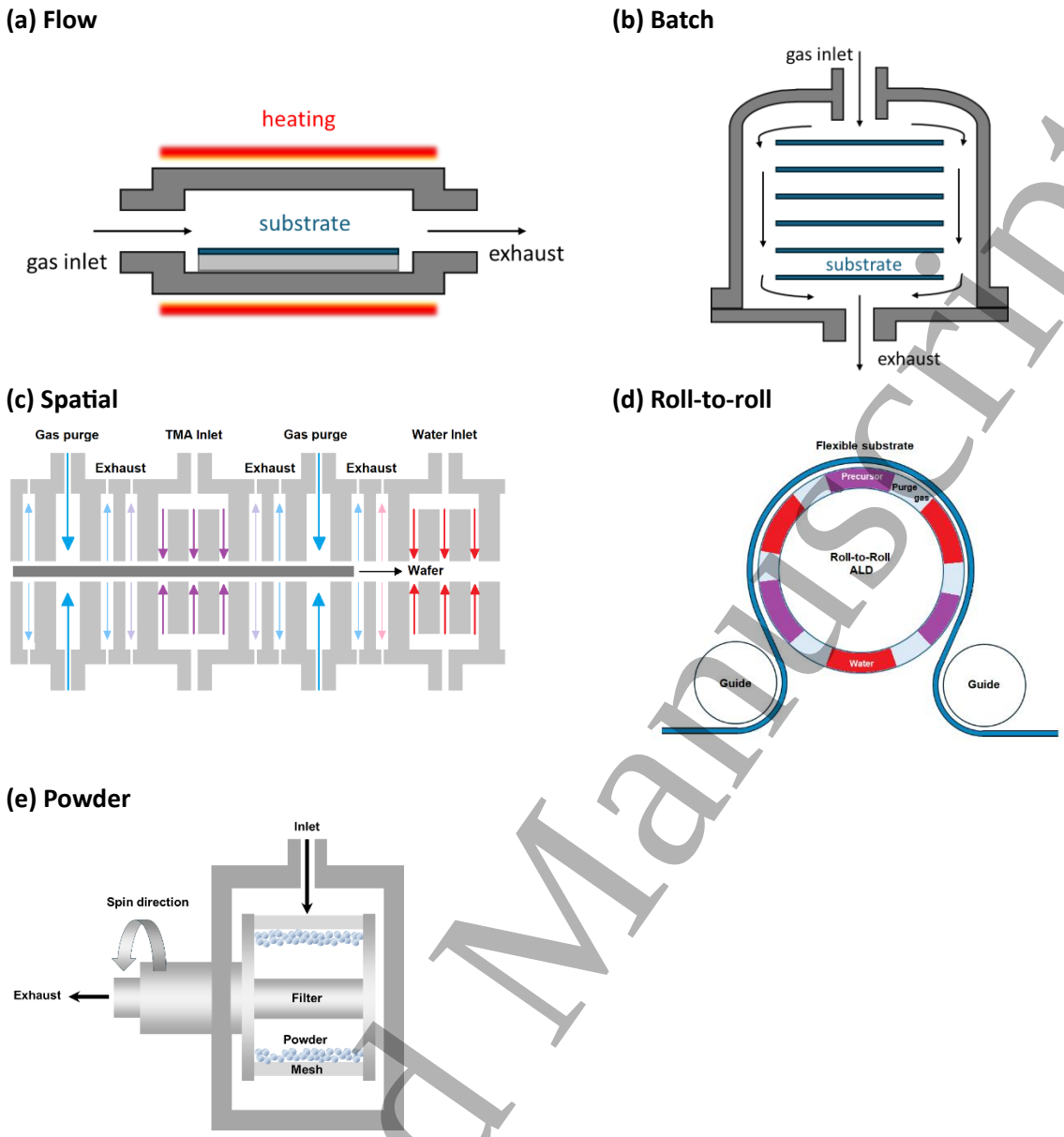


Figure 1. Schematics of five main types of ALD technology available to coat various materials. (a) flow – adapted from [2], (b) batch – adapted from [2], (c) spatial – adapted from [16], (d) roll-to-roll – adapated from [17] - and (e) powder - adapted from [18].

Concluding Remarks

Atomic layer deposition can enable electromagnetic (EM) functionality through the deposition of conductive, magnetic and dielectric films, and can be combined with other manufacturing techniques (e.g., additive, subtractive) to achieve new functionality or enhance metamaterial activity. As such, a multitude of existing and new ALD thin film coatings could be utilised to add EM functionality to a large variety of 3D and porous structures or flat surfaces (*i.e.,* metasurfaces). In such cases, the dielectric, conductive or magnetic films are deposited onto a surface and selectively removed (*i.e., via* subtractive manufacturing such as lithography) to realise periodic structures, *e.g.*, for fabrication of mm-wave photomodulators [10]. Although growth rates currently offered by conventional ALD are relatively slow, there exist a multitude of ALD technologies that already suit a larger variety of metamaterial applications. Nevertheless, recent advances in precursor design, reactor engineering, and process parameter control have significantly improved film quality and uniformity, even in scalable configurations such as roll-to-roll systems. As such, while challenges remain—as in any rapidly evolving fabrication technique—they do not fundamentally limit the applicability of ALD to metamaterial systems, but rather represent active areas of ongoing research.

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7. Subtractive manufacturing of electromagnetic metamaterials from microwave to terahertz

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Status

Metamaterials have been engineered to control electromagnetic waves in ways that natural materials cannot, across a broad spectrum from radio frequency (RF) to optical frequencies. This section will focus on electromagnetic metamaterials from RF/microwave to terahertz frequencies (i.e. GHz-to-THz), typically characterised by feature sizes larger than micrometres, whereas Section 8 will focus on photonic metamaterials on the nanoscale.

Conventionally and typically, the periodic patterns and structures of electromagnetic metamaterials are formed by selectively removing materials from thin films, laminates or bulk substrates. These are referred to as 'subtractive electromagnetic metamaterials' to distinguish from their 'additive' counterparts where structures are formed by sequentially adding/printing materials layer by layer. Common subtractive approaches include photolithography, etching (wet etching, reactive ion etching), mechanical machining (milling, drilling) and laser-based machining.

Subtractive manufacturing is still the prevailing fabrication method for electromagnetic metamaterials, especially for planar structures whether they are on a single or multiple, stacked layers. There are good reasons for that. Firstly, this fabrication method offers superior feature resolution and dimensional accuracy to additive or formative techniques. Depending on the operation frequencies/wavelengths (and therefore feature sizes), there are several established techniques, from printed circuit board [1] (PCB, with feature size from mm down to tens of um) to photolithography [2] (um feature), as shown in Fig. 1. Secondly, subtractive manufacturing is fast, especially for PCB and photolithography due to their exposure-based parallel processes. Note that speed is often a relative term, depending highly on

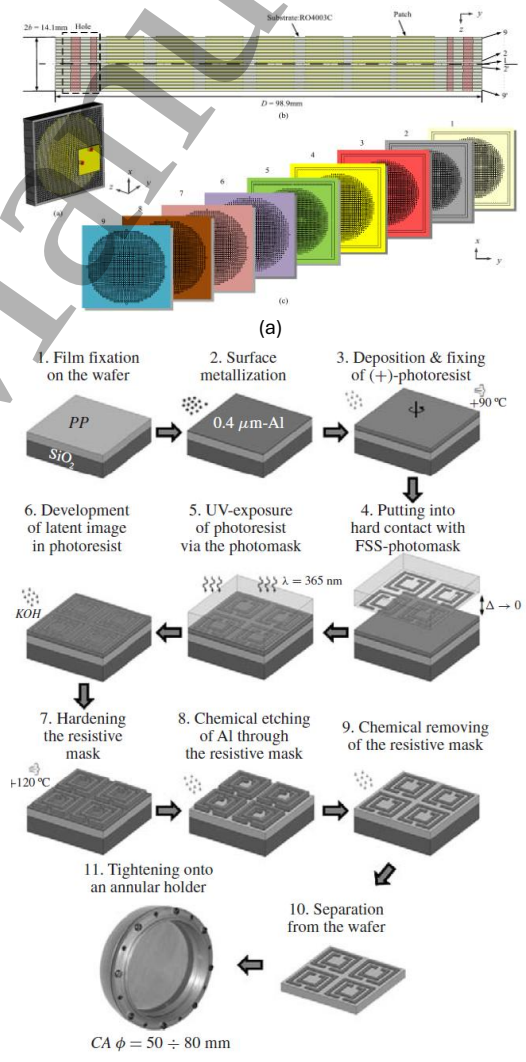


Figure 1. Metamaterials manufacturing by (a) Printed circuit board technique [1]; (b) Photolithography [2].

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the application and scale of the operation. The precision, speed, and process maturity (from electronic and semiconductor industry) make the subtractive approach most suitable for large scale production.

PCB process is a cost-effective, versatile, and scalable technique. Most of the RF and microwave metamaterials are based on this. Photolithography offers much higher manufacturing accuracy and has been mostly used for millimetre-wave, sub-millimetre-wave and terahertz metamaterials. Laser (micro)machining is a writing-based method and has been used in maskless direct-writing or to pattern PCBs or thin films for metamaterials.

Current and Future Challenges

Despite the wide adoption of subtractive manufacturing, challenges remain in scaling up, reducing manufacturing costs, and enhancing capability.

Scale and stack: On the one hand, RF/microwave metamaterials are generally large, in the order of tens of centimetres to meters. This requires large scale production capability. Some functional metamaterials may need multiple boards tiled together. Maintaining consistency across larger areas remains a manufacturing challenge. On the other hand, metamaterials are taking increasingly complex structures often configured in multiple layers. Multilayer PCBs have become increasingly available. However, the inter-layer alignment and interconnection increase the manufacturing complexity and cost.

3D structures: Most of the photolithography processes are designed for 2D structures on substrates. The depth dimension is being increasingly explored for new functionality and performance enhancement. For example, thick dielectric-free metamaterials show lower losses [3]. Features along the third dimension have also been used to alter the phase and/or miniaturise the unit cells. However, substrative manufacturing for 3D metamaterial is a more involved process and there are not many tools available.

4D metamaterials: These are a new class of metamaterials that can adapt or change their properties dynamically. These are often termed as: programmable/reconfigurable/tunable metamaterials [4], intelligent/smart metamaterials, or, among the most popular in the field currently, reconfigurable intelligent surfaces (RIS) or intelligent reflecting surfaces (IRS) [5]. The manufacturing of these metamaterials requires the incorporation of switches (e.g. diodes, MEMS) or varactors for controlling the frequency, mode, polarisation, phase, or amplitude of the constituent unit cells. A functional 4D metamaterial device often requires a very large number of such control elements. Metamaterials with embedded signal processing capabilities have also been reported [6]. The inclusion of the 'active' elements in metamaterials inevitably increases the manufacturing complexity and cost, often significantly, and reduces the production yield.

Advances in Science and Technology to Meet Challenges

PCB technology constantly evolves in their scaling and multilayer capability. When it comes to millimetre-wave metamaterials, high-precision PCB, through-silicon-via (TSV) and through-glass-via (TGV) processes can be applied [7]. Nanoimprint lithography may be used to manufacture micrometre features over a large scale and at speed for terahertz metamaterials [8].

Micromachining and MEMS techniques, such as deep reactive ion etching [9], thick photoresists [3] and laser micro-process [10], can produce true 3D structures with depths of hundreds of micrometres. Among others is hybrid subtractive-additive manufacturing [11], where the advantage of both worlds (high precision and flexibility) can be leveraged to produce complex and intricate

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structures. For example, the base structures may be additively manufactured while subtractive processes are applied for fine-tuning.

The more advanced functional metamaterials, such as RISs and computational metamaterials, demand new manufacturing, integration and assembly approaches as well as the use of new materials. Liquid crystals, graphene, ferroelectrics, liquid metals, and phase change materials [12] may be integrated in metamaterials to enable real-time control over their properties.

Concluding Remarks

Subtractive manufacturing provides a robust and well tested platform and is still the workhorse for producing metamaterials for their fabrication precision, speed and scalability. Increasing the cost-effectiveness and enhancing the scaling capability will remain the key drives for the advancement of subtractive manufacturing with the increasing commercial adoption of metamaterials. The emergence of new metamaterial concepts and demand for more advanced functionalities will create new manufacturing challenges. Hybrid manufacturing approaches, combining subtractive, additive and formative means, may provide new solutions. The integration of new materials is expected to be a main area for innovation. In any case, subtractive manufacturing will continue playing a major role in the future development and deployment of electromagnetic metamaterials.

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8. Subtractive and formative manufacturing of photonic metamaterials

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Status

Photonic metamaterials are a class of artificial materials designed to manipulate light typically with the wavelength below 1650 nm using periodic, sub-wavelength, structures [1]. Unlike conventional materials whose optical properties primarily arise from their chemical composition, optical response of photonic metamaterials is defined by the shape and distribution of its constituent nanostructures, enabling the creation of materials with tailor-made optical properties. Optical elements based on photonic metamaterials have already found their applications in a range of novel optical devices, including ultra-compact and efficient LIDARs and Time-of-Flight sensors and Augmented Reality (AR) wearables [2,3]. However, their widespread adoption is hindered by significant challenges in the manufacturing process: the creation of photonic metamaterials requires fabrication of complex three-dimensional (3D) nanostructures, see figure 1, over the area of several square centimetres with minimal deviation from the designed pattern. While manufacturing techniques originating from the semiconductor industry are capable of fulfilling these requirements, they are primarily developed for a layer-by-layer fabrication of planar nanostructures, thus significantly limiting the variety of achievable shapes.

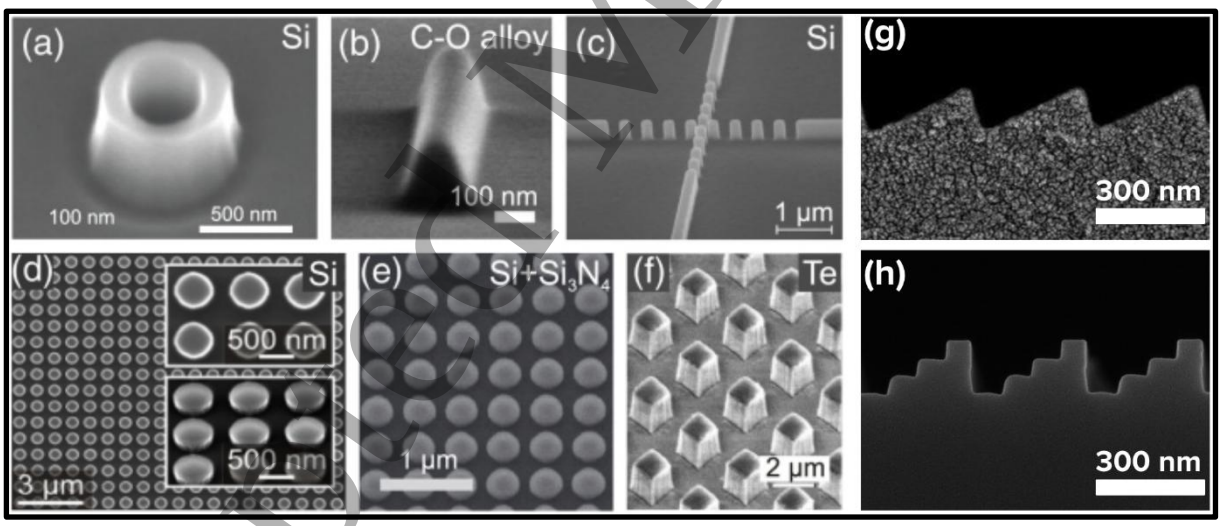


Figure 1. Examples of photonic nanostructures with complex 3D shapes. Reprinted with permission from: (a) Ref. [4], (b) Ref. [5], (c) Ref. [6], (d) Ref. [7], (e) Ref. [8], (f) Ref. [9],.

Current and Future Challenges

While a vast range of photonic metamaterials boasting diverse functionalities have been proposed and patented, only a few have found their way into the end-user market. The primary obstacle hindering commercialisation of photonic metamaterials is the absence of established design-for-manufacturing (DfM) methods, resulting in designs that often do not account for manufacturing constraints. The implementation of practical DfM guidelines would enable the development of nanostructures that are both attainable and suitable for mass production, allowing them to transition from research

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prototypes to commercial products. A notable example of such products are diffraction metagratings used in AR headsets to couple image-bearing optical rays in and out of transparent waveguide combiners [10]. Unlike conventional diffraction grating couplers, metagrating employed in the AR imaging waveguides are composed of individual nanoscale elements with intricate 3D shapes. Each of these elements acts as a sub-wavelength antenna with the optical response of the metagrating determined by the convolution of the interference pattern of the entire grating and the radiation profile of individual grating elements. By optimising their shape and spatial distribution, the dependency of optical response on the wavelength and incident angle of the image-bearing rays can be reduced, suppressing chromatic and angular aberrations.

Another example are metalenses, optical elements designed to manipulate the properties of an incoming light wavefront using a quasi-periodic array of nanoantennas. Metalenses offer substantially reduced thickness compared to conventional refractive lenses and can combine multiple functionalities, such as phase and polarisation control, in a single element, thus enabling a substantially smaller size of the optical module. However, as metalenses suffer from strong chromatic aberrations, their application is mostly limited to single wavelength systems [11]. Examples of successful integration of metalenses into commercial devices include miniaturised Time-of-Flight and LIDARs sensors used in mobile devices and robotics to accurately map the surrounding 3D environment [2].

Successful implementation of photonic metamaterials into consumer devices is dependent on a thoughtful design of the metamaterial components, which should take into consideration available manufacturing methods and production costs. In the following sections, we briefly explore manufacturing methods that are suitable for the large-scale production of photonic metamaterials and discuss their advantages and limitations.

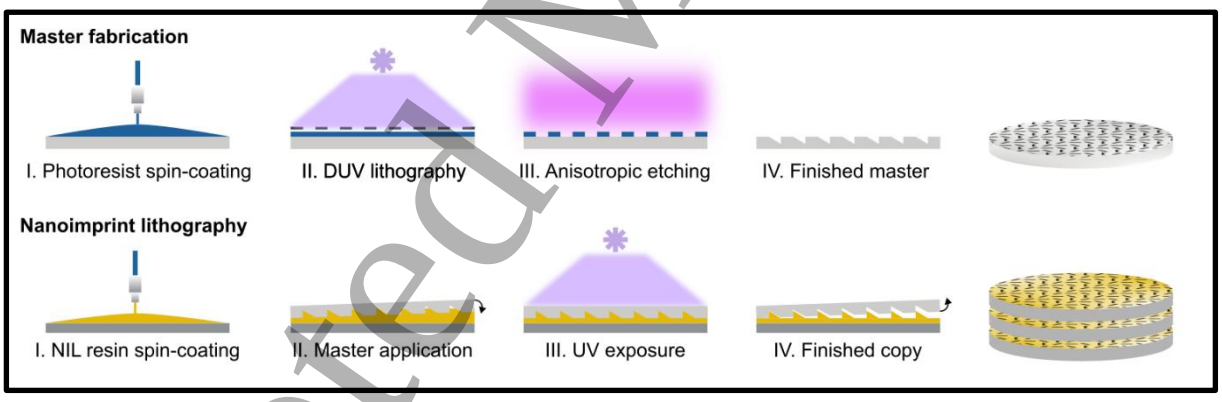


Figure 2. Schematics of the key steps of (top) fabrication of master stamp using DUV photolithography and (bottom) replication of the stamp using nano-imprint lithography.

Advances in Science and Technology to Meet Challenges

Formative methods

In nanophotonics, formative manufacturing methods typically refer to application of force, heat, pressure, or their combination to shape the surface of a substrate into the desired profile. Arguably, the most developed and widespread formative replication technique is nano-imprint lithography (NIL) [12], which involves replication of nanopatterns from a parent substrate (so-called master stamp) through mechanical shaping of a polymer resin layer on a target substrate. The key advantage of this approach is that it provides means to decouple the difficulty of attaining complex 3D shapes from the large-scale production of the final product: although the manufacturing of the complex 3D shapes

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required for photonic metamaterials remains a challenging task, this has to be done only once during master stamp fabrication.

Master stamps for NIL are typically fabricated using electron-beam lithography (EBL) or Deep-UV (DUV) lithography. Common steps of the master fabrication process are illustrated in figure 2: first, a target substrate (typically Si or SiO_2) is coated with a suitable photoresist, and the desired metamaterial pattern is exposed in the resist layer using EBL or DUV lithography. The resist layer then acts as a mask for anisotropic etching, enabling the pattern to be transferred into the target substrate. Sloped structures, often required for photonic metamaterials, can be achieved using angled ion-beam etching or preferential chemical etching along the crystalline lattice [13].

A typical NIL replication process starts from spin-coating or ink-jetting of the imprintable polymer, called NIL resin, onto a rigid substrate followed by a pre-bake to evaporate solvents and increase resin viscosity for the NIL process (if required). The maser stamp is then pressed into the NIL resist layer, leading to a direct pattern transfer through mechanical shaping. A thin residual layer of NIL resist is left between the stamp and the substrate, acting as a buffer to avoid direct contact of the master stamp relief nanostructures with the imprinted substrate. After the patterned NIL layer is hardened by UV or thermal curing, the master stamp is removed, leaving an imprinted polymer pattern on the substrate. Nano-imprint lithography allows for replication of nanostructures as small as 5-10 nm with the standard deviation of the critical dimensions below 1 nm [14].

Since the nanostructures are formed directly in the polymer layer, the resins used for NIL replication must have a suitable refractive index, as well as satisfy NIL-specific requirements: they should come in a liquid form so that they could be applied by spin-coating or ink-jetting, and have a suitable viscosity to flow and fill-in the master pattern during the replication process. Further, the surface properties of the cured NIL resin should allow for a smooth detachment of the stamp without causing damage to the replicated nanostructures. These requirements make the development of the NIL resins a rather challenging task. Several commercial companies were successful in achieving NIL resins with RI in the range of 1.2-2.0 by creating hybrid polymer materials with added TiO_2 and ZnO_2 nanoparticles [15, 16].

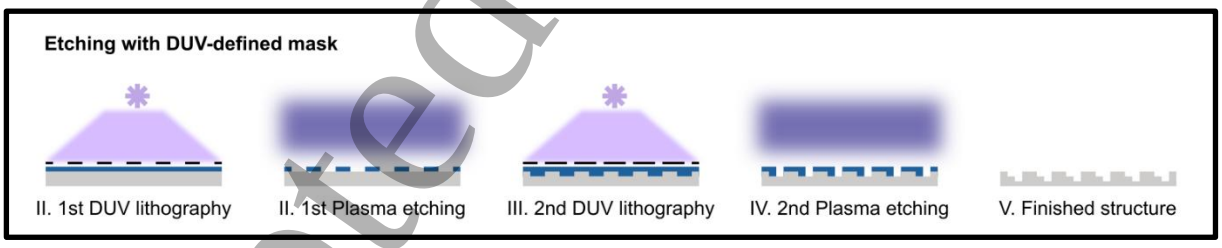


Figure 3. Key steps of fabrication of photonic metamaterials using multi-step DUV photolithography and plasma etching.

Subtractive methods

Subtractive manufacturing involves selective removal of material from a target substrate to create desired patterns on its surface. Large-scale manufacturing of nanostructures using subtractive methods generally relies on plasma etching via a sacrificial mask which contains the required features of the target nanostructures. Sacrificial etching masks used in fabrication of semiconductor components are typically created using DUV and Extreme-UV (EUV) photolithography. Both of these techniques can create nanoscale patterns on silicon wafers or other substrates, but they are generally limited to binary structures, i.e. comprising only two distinct height levels. When applied to

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manufacturing of photonic metamaterials, both DUV and EUV lithography can be used to produce stepped nanostructures which approximate target 3D shapes using multiple consecutive etchings (see figure 3 and figure 1 (g)-(h)). The accuracy of this approximation is directly linked to the number of steps used to mimic the desired nanostructure [17]. Since the patterns employed in photonic metamaterials are sub-wavelength, this approach requires complex multi-step lithography with precise alignment of the etched layers down to a few nanometers. Owing to technical and commercial limitations, subtractive manufacturing using DUV and EUV lithography is only suitable for photonic nanostructures comprising a maximum of two or three levels.

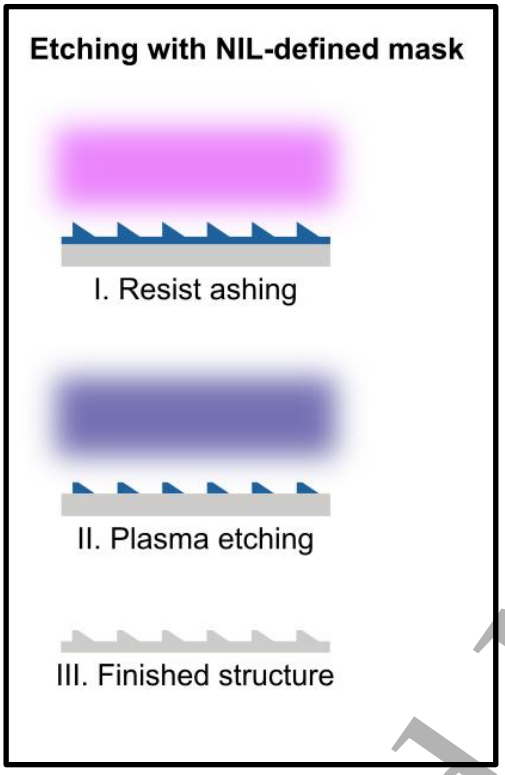


Figure 4. Etching of the photonic nanostructures using sacrificial mask created by nano-imprint lithography.

By employing NIL replication, it is possible to create sacrificial masks suitable for the fabrication of complex 3D nanopatterns in a single step [18], therefore streamlining the manufacturing process. Figure 4 illustrates fabrication of photonic nanostructures using NIL-mask-assisted plasma etching. First, the nanostructure pattern is transferred into a polymer resin coated on the surface of a target substrate using NIL. The remnant layer left underneath the pattern created by the NIL process is then removed using plasma etching. Finally, the patterned resin layer is used as a mask for plasma etching, directly transferring the photonics nanostructure pattern into the target substrate or optical coating. Although this approach simplifies the fabrication process by allowing single-step manufacturing of 3D shapes, it presents its own challenges. First, the thickness of the remnant layer under the imprinted pattern needs to be minimised, so it can be removed with negligible degradation of the pattern features. Secondly, a suitable etching process should be developed, capable of translating a variety of 3D shapes present in the sacrificial mask into the substrate with minimal distortions of their critical dimensions. This can be particularly challenging as different elements of the same nanostructure often show drastically different etching rates. If such distortions are unavoidable, they should be compensated in the master stamp, provided that deformations of the original pattern are known and consistent within the manufacturing process.

Concluding Remarks

Manufacturing of photonic metamaterials presents a formidable challenge, demanding the development of new patterning processes which are better suited for fabrication of complex nanoscale elements over large functional areas. While nanofabrication techniques inherited from the semiconductor industry are potentially capable of achieving the required patterning area and resolution, being designed primarily for planar structures, they struggle to produce component 3D shapes of photonics metamaterials, leading to reduced device performance. Nano-imprint lithography presents an example of pioneering formative techniques tailored specifically for large-scale and cost-effective fabrication of photonic nanostructures. Although the first commercial products employing

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photonic elements manufactured using this method have recently entered the market, its widespread adoption is still limited by achievable refractive indices of imprintable polymers. This limitation can be overcome by combining nano-imprint lithography with conventional subtractive techniques. However, developing an etching process capable of transferring photonic nanostructures from nano-imprinted sacrificial masks into an optical coating poses a significant challenge. Nevertheless, once suitable etching recipes are developed and adapted for mass production, they will likely find their application beyond nanophotonics, e.g. enabling the manufacturing of novel electronic and micro-electromechanical devices beyond the current planar technology.

Acknowledgements
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9. Passive acoustic metamaterials using additive manufacturing

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Status

Acoustic metamaterials (AMMs) [1-3] are artificial structural arrangements consisting of carefully designed acoustic elements (unit cells), that manipulate acoustoelastic to achieve desired extraordinary effective properties, such as negative effective density or bulk modulus [4,5]. This allows enabling functionalities like exceptional refraction, absorption, reflection, transmission suppression, and bandgap formation [6], into perfect absorbers, acoustic lenses and cloaks [4] across applications ranging from military camouflage to medical imaging, and communication [3].

Lee et al. [6] classify AMMs according to three principal criteria. The first structure-acoustic field interactions, whereby systems are differentiated on the basis of their geometric configuration, including 2D metasurfaces and 3D bulk architectures. The second criterion pertains to their acoustic control mechanism, encompassing local resonance, phase modulation, amplitude attenuation, and structural reconfiguration. The thirds relates to their functional responsiveness and interrelated aspects, defined by the manner in which the system responds to external stimuli. This framework introduced notions such as responsiveness and tenability, through which AMMs may be further distinguished as passive, active, or adaptive systems.

The emergence of additive manufacturing in the 1980s facilitated the exploration of metamaterials [2], and advancements in lithography and nanofabrication have further accelerated their development, to produce increasingly complex designs and structures [1].

Current and Future Challenges

Among various types of acoustic materials, the most sought-after are sound-absorbing materials used in vibration and noise reduction engineering. Phononic crystals [1], create of a wide bandgap, maximising the acoustic impedance mismatch between the solid and air, enable effective sound absorption, filtering, and isolation and may even exhibit negative index behaviour at specific frequencies. As AMMs have subwavelength dimensions, they can reach perfect broadband sound absorption while minimizing volume [3].

Based on how they manipulate acoustic waves, AMMs can be classified into four types: (a) membrane-type (b) Fabry-Perot-type, (c) Helmholtz-type, and (d) ventilated-type absorbers. Other innovative AMMS include acoustic black holes [8], which use exponential decay of wave amplitudes to absorb sound efficiently, and acoustic cloaks [9], which bend and redirect sound waves to render objects acoustically invisible. These cloaks have potential applications [3] in underwater camouflage, sonar enhancement, acoustic imaging, and vibration, although challenges persist, particularly with 'illusion cloaks' and cloaking near curved boundaries [9].

Topological AMMs [3] exploit symmetry breaking and material structure to control wave propagation. Topological Insulators [10] and Acoustic Lenses [11], manipulate sound using gradient index materials, enabling applications in medical ultrasound imaging, sonar, and industrial inspection.

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Acoustic diodes [12], use asymmetric structures for unidirectional sound transmission, controlling wave flow direction.

Additive Manufacturing Methods have evolved, allowing the printing of different forming material types (wire -, liquid -, powder -, mixed - based) containing metals, polymers, ceramics and hydrogels, enabling the production of complex 3D structures with resolutions ranging from the meter-scale [4] to 10s of nm scale [2]. Techniques include vat polymerization, powder bed fusion, extrusion/deposition, hybrid methods, and atomic scale techniques [2]. Atomic scale techniques (ACMS) such as Site-Selective Chemical Vapour Deposition (CVD), Area Selected Atomic layer deposition (ALD), electrodeposition, laser-assisted synthesis, and selective deposition/printing techniques allow precise 2D material control, but face scalability and material consistency challenges. While micro-AM methods excel in nano-scale precision, they struggle with larger-scale fabrication [4]. However, challenges still exist in terms of production costs, manufacturing efficiency, and material selection [7].

Advances in Science and Technology to Meet Challenges

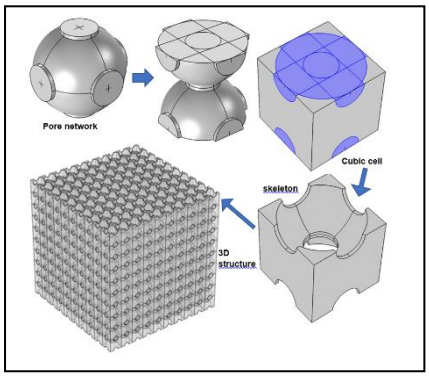


Figure 1. Pore, interconnecting network and skeleton design within a porous 3D structure. Adapted from Zieliński et al [13].

A key challenge in the additive manufacturing (AM) of acoustic metamaterials (AMMs) lies in the complexity of their multiscale structures and the limited resolution capabilities of low-cost AM technologies. AMMs often integrate large-scale structures intertwined with micron-scale components, requiring high precision across scales from micron to centimetres [2]. These demands, along common imperfections in AM – such as porosity and microporosity [13] - limit the fabrication of pore networks analogous in scale and performance to those in conventional broadband sound-absorbing materials [2].

Kennedy et al. [14] investigate benchmark AMM structures fabricated through various AM methods, addressing design, production, modelling, and validation. Their design, featuring an interconnected network of resonant chambers within periodic cubes (figure 1), demonstrated that while all printing methods aligned reasonably with numerical models, challenges remained in achieving geometric fidelity and optimal surface texture, especially for intricate geometries. Polymer-based techniques like SLA showed potential for high-precision fabrication but faced difficulties such as incomplete resin removal, with poor print quality significantly impairing acoustic performance. This highlights both the potential and current limitations of AM for AMMs and emphasizes the need for more affordable, versatile 3D printing solutions.

Advancements in micro- and nanofabrication are crucial to enable high-frequency AMMs, which are vital for enhancing medical ultrasonic imaging and non-invasive surgical tools. Furthermore, optimizing AMM design requires a deep understanding of the relationship between structure, properties, and function. This has led to the growing integration of digital tools and artificial intelligence (AI) for design automation, predictive modelling, and performance optimization [15]. A holistic approach—encompassing fundamental science, functional performance, manufacturing methods, and real-world applications—is essential to fully leverage AMMs in industrial contexts [1].

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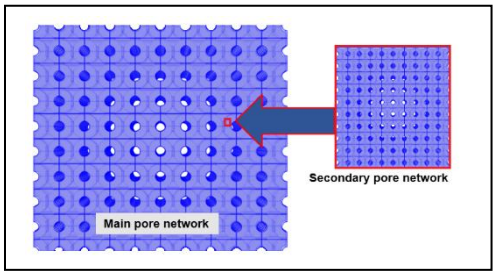


Figure 2. Scheme for a double-porous media. Adapted from Zieliński et al [13].

Zieliński et al. [13] demonstrated the advantages of 3D-printed double-porosity structures (figure 2), where a primary microporous network is enhanced by an intentionally microporous skeleton. This design improves permeability contrast and therefore leads to additional broadband sound energy dissipation via pressure diffusion [16].

Akram et al [15] developed an AI-based design technique for highly broadband AMM for target frequencies, optimising computational costs while ensuring ease of fabrication, by employing NSGA-II alongside a machine-learning model trained on data from FEA of design variations based on the raw hybrid model.

Recent advances in AM, including multi-material printing, microprinting, and atomic-scale techniques show promising directions. The transition from layer-based to like voxel-based printing allows material control at the microscale, while volumetric 3D printing joined with AI optimisation techniques boosts speed and efficiency [15, 17]. Future trends aim for ultra-large, ultra-fine, multi-material constructs with higher resolution and faster production times [17], pushing AMMs closer to widespread practical deployment.

Concluding Remarks

The exploration of hybrid models that amalgamate efficient atomic and micro-printing techniques could be the solution to cost effective production of multiscale AMMs. This innovative approach holds immense promise for advancing additive manufacturing (AM) technology to new heights. By seamlessly integrating atomic-scale precision with the versatility of micro-printing and AI optimisation techniques, researchers can potentially surmount existing limitations in resolution and material diversity, thereby unlocking a realm of possibilities in the fabrication of complex acoustic metamaterials (AMMs) with customized properties. Moreover, the development of novel fabrication methods through hybrid models could lead to enhanced efficiency and cost-effectiveness, addressing pivotal challenges in AM. As we venture further into the realm of AM, the integration of atomic and micro-printing approaches stands as a beacon of opportunity, poised to propel innovation and drive transformative change across various industrial sectors.

Acknowledgements

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10. Active and multi-material acoustic metamaterials fabricated via additive manufacturing

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Status

The advantages of additive manufacturing (AM) for the fabrication of acoustic metamaterials (AMMs) are consistent with those pertaining to the wider metamaterial family. In recent years, a huge variety of AMMs have been produced using many of the conventional AM techniques, detailed summaries of which can be found in several comprehensive reviews, with sections or entire publications dedicated to acoustic-specific applications [1]. The choice to employ AM technology tends to be driven by the required AMM design; the main factors to consider are the minimum printable feature size (and thus the frequency of operation), the ease of manufacture, and material functionality or availability. The capacity of AM technologies to deposit multiple materials simultaneously, within a single process, and to embed one material within another, has huge potential for the fabrication of multi-material and active AMMs with embedded electronics, although this area remains largely unexploited at present. This section focuses on the current status, challenges and the opportunities within the manufacturing of multi-material-based AMMs and active AMMs.

The majority of additively manufactured AMMs are, at present, single-material, passive prints. Coiled structures are one representative example, for which the curved, folded, or tortuous geometries required to direct acoustic waves render the designs extremely difficult, if not impossible, to fabricate using traditional methods [1]. These structures have been produced using singular materials via fused deposition modelling (FDM) [2], material jetting (MJ) [3], digital light processing (DLP) [4], and stereolithography (SLA), where coiled-up space was also used to form a gradient index [5].

Gradient index devices themselves form another notable class of AMMs for which the high degree of spatial control, and in particular, the multi-material capability offered by AM is especially appealing; these are functionally-graded structures across which the acoustic refractive index can be spatially varied for enhanced manipulation of sound waves [6]. This gradient is typically obtained through local changes in geometry, as in the case of single-material Luneburg lenses, which have been additively manufactured via MJ [7], selective laser melting (SLM) (figure 1a) [7], and SLA [8]. However, functional grading may also be achieved through material property or compositional changes, as shown in reports of acoustic black holes enabled by multi-material jetting via Polyjet™ technology using combinations of commercial VeroWhitePlus, VeroClear and TangoPlus photopolymers (figure 1b) [9,10]. Tunable structural vibration absorbers, exploiting both geometric and material property changes within a single process, have also been fabricated via MJ in the form of multi-material resonators, which further incorporate a geometrically complex coiled design together with a material gradient [11].

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The conventional, passive AMM systems described above possess a fixed structure, and thus, a pre-defined acoustic response which cannot be altered without fabricating an entirely new device. In contrast, the functionality of active AMMs may be varied, either via structural rearrangement or through the use of external stimuli to tune local AMM properties, including the use of thermal, mechanical, electrical and magnetic signals to enable a dynamic response to ever-changing acoustic environments [12]. At present, any additively manufactured active AMMs tend to achieve tunability or dynamic control via the former method i.e., a physical, mechanical rearrangement of the printed structure(s), often referred to as 'reconfiguration'. Examples include tunable acoustic beam shaping achieved by the twisting of 3D-printed moiré metasurfaces (figure 1c) [13], 3D-printed resonators which are rotated and/or removed from a noise-insulating AMM chamber to tune to an additional configuration [14], and the longitudinal movement of FDM-fabricated coiled-up channels for adaptable sound absorption performance in ultra-thin AMMs [15]. In some reports, printed AMMs are both multi-material and active, as in the case of multi-material origami metasurfaces, produced using PolyJet™ MJ technology, which demonstrate distinctive reflective acoustic behaviours upon the collapsing or deploying of the individual binary-switchable origami units (figure 1d) [16]. The use of external stimuli is a more dynamic approach to tunability as compared to mechanical reconfiguration, and can be controlled remotely, with faster response times [17], but further work is needed to use AM to its full advantage in this area. At present, external signals are typically utilised to control only part of the response tuning process, e.g., in bistable sound absorbers, fabricated via FDM using shape-memory polymers, which may be returned to their original configuration under temperature stimuli, but which must first be deformed using physical force (figure 1e) [18]. In other cases, active AMM control involves the incorporation of additional, non-additively manufactured electromagnetic components and devices, such as commercial piezoelectric patches and negative capacitance circuits connected to switchable elastic waveguides in order to tune their wave propagation direction [19].

Current and Future Challenges

AM has become increasingly applicable to AMMs fabrication [9, 11], catering to a broad spectrum of material requirements (metallic, polymeric and composites), design intricacies (lattice, functionally-graded structures/optimised topologies), and resolutions (100 nm to 10 mm) [20]. Despite these advancements, the AM of materials with different elasticities and densities in a single print bed remains a challenge. These material properties, particularly elasticity, density, and damping, influence acoustic performance in AMMs, as they govern key behaviours such as sound absorption, impedance matching, and transmission-loss characteristics [21,22]. Thus, precise control of these properties is essential in AM-based fabrication. While AM has shown promise in creating intricate structures without the need for support materials [5], and variations in elasticity (e.g., MJ [9,11]) with multi-material capability, achieving significant density variations presents further challenges. Recent approaches include introducing porosity within materials to achieve effective density variation even when using a single material feedstock [23]. Majorly, AM of materials with varying densities is constrained by material compatibility and post-processing challenges. For example, co-fabricating metallic and polymeric structures is complicated by the fundamentally different processing requirements involved, such as selective sintering or melting of metallic powders versus crosslinking or polymerisation of resins, which cannot be accommodated within a single print bed. Having said that, multi-material AM techniques, such as MJ, offer promising routes for developing AMMs with unique material configurations, and demonstrations of multi-material (soft and rigid) acoustic black holes [9] and resonators with tunable natural frequencies [11] have been reported. AM plays an

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important role in the development of acoustic metamaterials, particularly for complex, highly customised architectures and multi-material systems. However, its current technology readiness level and production throughput may still limit its suitability for large-scale manufacturing. Indeed, only limited patent activity and commercialisation has been observed in this field [24,25]. As AM technologies continue to mature, their scalability and cost-effectiveness are expected to improve.

Moreover, metrology, including measurement of mechanical, morphological (internal impurities and layering effects), and fatigue properties play vital roles in determining the performance of AM-produced components for AMMs. Additionally, for multi-material structures, understanding material interfaces becomes paramount [26]. While the realisation of materials with virtually unlimited geometries is achievable, optimisation with modelling and simulation techniques is essential for fully taking advantage of the potential of AM-manufactured AMMs [27].

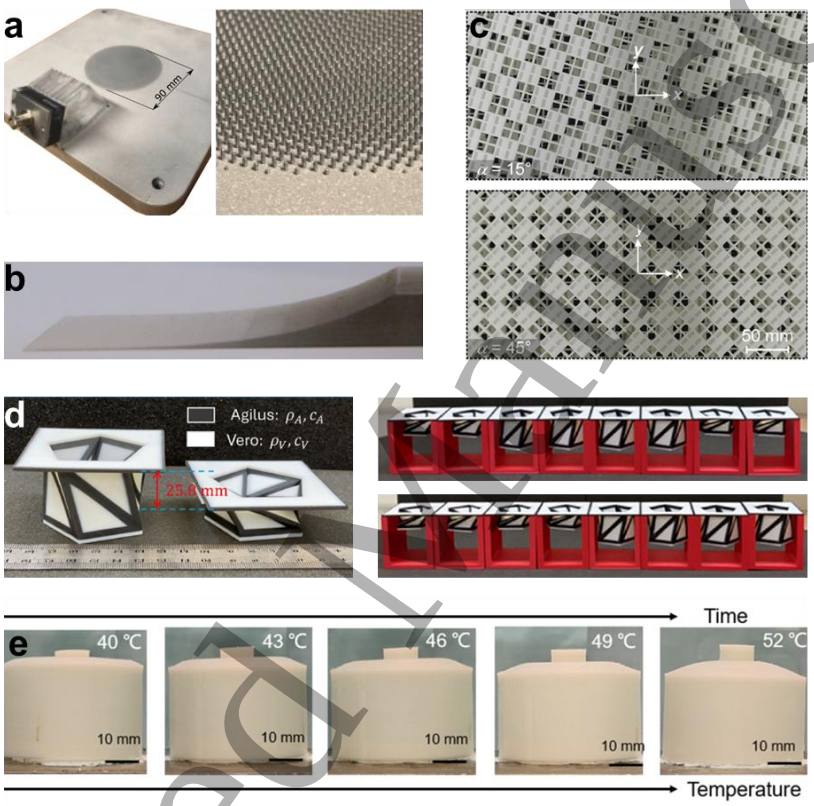
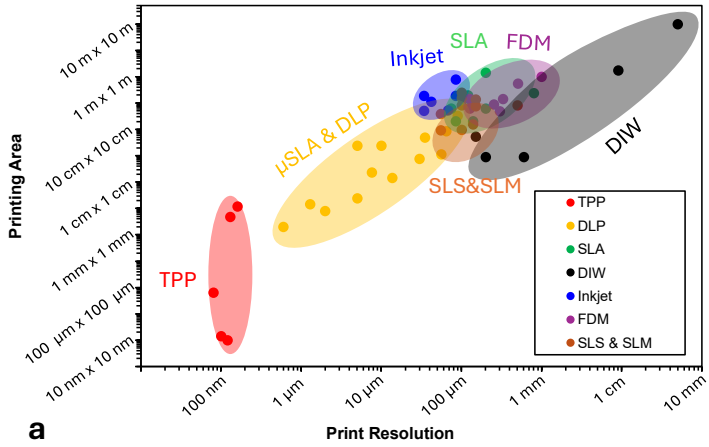


Figure 1. Additively manufactured AMMs. (a) Single-material, passive SLM-printed Luneburg lens on the surface of an aluminium block [7]. (b) Multi-material, passive acoustic black hole via MJ [9]. (c) Active (mechanically reconfigurable), single-material twisting moiré metasurfaces [13]. (d) Active (mechanically reconfigurable), multi-material binary-switchable origami units [16] and (e) Active (thermally reconfigurable), single-material bistable sound absorbers [18].

Looking ahead, to realise an elasticity and density variation, a potential solution involves utilising multi-material and scalable printing, such as inkjet, using nanoparticles as feedstock material together with polymeric materials. A more innovative approach is to actively change material properties, such as stiffness and damping, 'on demand' through AM of active or smart materials, such as those responsive to magnetic and electric fields, or heat stimuli [28] (e.g., magnetic elastomers, shape memory polymers, electroactive elastomers). The realisation of intelligent systems via AM demands the development of new feedstock materials, metrological techniques for investigating material interfaces [29], and advanced design and simulation techniques [9] for incorporating multi-material and stimuli-responsive materials. On the other hand, scaling for large-area applications (e.g., marine and aerospace where sound is highly prevalent) is challenging due to the limited build volumes

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of current AM techniques. Nevertheless, some AM techniques such as ink jetting show scalability potential for mass-producing metamaterials, offering drop-on-demand and co-deposition of multi-materials for large-scale applications.



AM Technique	Multi-Material Capability	Scalability
FDM	Yes	Limited
SLA/DLP	Yes (Lab Prototypes)	Limited
Ink Jetting	Yes	Yes
DIW	Yes	Limited
SLM/SLS	Yes*	Limited

*Recent (Aconity3D GmbH)

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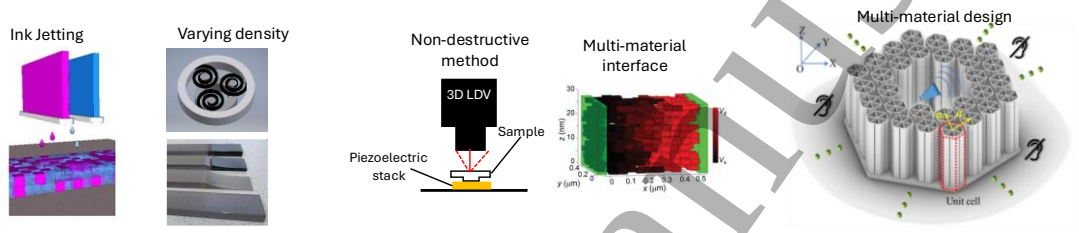


Figure 2. (a) A graph illustrating the relationship between resolution and print size across various AM methods redrawn from [20] (b) A table showcasing multi-material and scalable AM methods. (c-e) Summary of potential areas for future research and development of AM-based AMMs. (c) Multi-material and Scalable AM [9, 11], adapted under Creative Commons CC-BY license Copyright Frontier 2022, and Elsevier 2024, d)) Metrology of AM parts [24], adapted under Creative Commons CC-BY license Copyright Wiley 2021 and (e) acoustic MM design and simulation [25], adapted with permission Copyright Elsevier 2024

Advances in Science and Technology to Meet Challenges

Continuous efforts have been made for the development of multi-material printing platforms, enabling the fabrication of functionally-graded structures within a single component. Material extrusion AM techniques including inkjet, direct ink writing (DIW) and FDM have shown great promise for multi-material printing. These methods allow for the precision deposition of materials with varying functionalities, offering the flexibility to integrate materials with different mechanical, thermal and electrical properties. Significant progress has been made in both equipment design and material feedstock development. For example, material extrusion AM platforms now feature multiple nozzles capable of accommodating diverse functional materials [29]. Photopolymerisation-based AM processes including SLA, DLP and two photon polymerisation (2PP) have also made considerable progress. New equipment designs, featuring multiple resin vats and coupling with different AM techniques such as DIW and FDM, enable the movement of vats containing different resins or allow the build platform to shift between different resin vats, facilitating the printing of multi-material structures [30]. Despite these advancements, controlling the interfaces between dissimilar materials and addressing post-processing challenges remain significant hurdles in multi-material printing.

Multiphysics simulation and inline metrology have emerged as essential tools to tackle these challenges. Multiphysics simulation integrates multiple physical phenomena to predict and optimise the behaviour of multi-material structures, enhancing the design and performance of complex

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components. Inline metrology with real-time monitoring of key printing and material property parameters, ensures dimensional accuracy and material consistency, improving quality control throughout the printing process. Also, artificial intelligence (AI) in AM processes can play a key role in the various stages of the manufacturing process, from design and simulation to real-time control and defect detection [31]. Continued efforts in both hardware and material design, coupled with Multiphysics simulation, metrology and AI-driven optimisation, are essential to enable high volume manufacturing of 3D architected structures, including metamaterials with functional gradation and complex geometry, ultimately realising their potential for large-scale, high-performance applications.

Concluding Remarks

In summary, future research in AM-based AMMs needs to focus on the advancements in active and multi-material AM techniques alongside scalable methods, the innovation of metrology tools, and the development of advanced design and simulation software for active and multi-material structures through multi-stakeholder collaboration. Initiatives such as those led by the UK Metamaterials Network are pivotal in fostering knowledge sharing, and consortiums involving academia, industry, and government stakeholders can effectively pool resources, share risks, and drive collaborative innovation in this field.

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11. Subtractive manufacturing for acoustic metamaterials

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Status

A comparison between additive manufacturing (AM) and subtractive manufacturing (SM) indicates that the latter is available for a much wider range of materials. Virtually anything can be subtractively manufactured, whereas AM is restricted to a much narrower range of material types. While AM can deal with higher levels of complexity in terms of shape etc, the finish of the final build sometimes needs to be improved if AM is used. Furthermore, SM can be a more rapid manufacturing method than AM, and the structural integrity in terms of mechanical and other properties is simpler to attain. The main problem facing the choice of SM technique is that many metamaterial designs are complex, and hence more suited in some cases to AM. Subtractive techniques remove material from an initial stock to produce the finished product, and include Computer Numeric Control (CNC) milling, Electric Discharge Machining (EDM), Laser Machining (LM), Water Jet Machining (WJM), Focussed Ion Beam (FIB) machining/milling, and Chemical Etching (CE). Here we highlight some possible designs and metamaterial substrates that could use subtractive methods more effectively. While SM techniques are often dismissed for the production of metamaterials [1], SM methods could allow the production of both 2D and 3D metamaterials.

Conventional subtractive machining can be used to manufacture acoustic metamaterials at low frequency, where the feature sizes would be larger. An example application is in underwater cloaking e.g. in hiding the presence of an object on the seabed [2]. Amongst other methods, LM is a good technique for producing intricate patterns in solid surfaces [3], and such techniques can be used to produce metamaterial surfaces that have adjustable acoustic properties. Laser focussing can also produce patterns within solid blocks of transparent materials such as polymers [4]. Direct laser cutting can also be used to make metamaterials based on origami-type geometries constructed from thin sheets [5]. It has been used, for example, to produce acoustic cloaking devices for use in air [6] which used a pyramidical acrylic structure.

WJM can be used for substrates where conventional machining is difficult and has the additional advantages that it does not introduce either heating of the sample or significant mechanical stress to the surrounding substrate [7]. This is of interest for acoustic metamaterials based on soft polymers and foams. An example is the creation of a focussing metamaterial based on a metallic foam-like structure [8]. It has also been used in cutting chiral structural patterns within rubber sheets as part of a system for vibration control containing additional metallic masses, and also for an aluminium structure with the same end-use [9,10].

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Fischer *et al.* [11] (see figure 1) have discussed various methods of fabrication of metamaterials. For example, CNC machining for larger structures, or FIB for much higher resolution [12] can create patterned sheets of metal which can be layered to form a metamaterial [13]. Pyo and Park [14] have reviewed fabrication strategies for metamaterials; further, the use of mechanical cutting to fabricate 2D auxetic patterns in polymeric films [15] and stainless-steel sheets [16] is possible. Also, the precision drilling of holes is in widespread use in printed circuit boards for electronics [17]. Mechanical drilling is possible routinely for 1 mm holes, whereas 200 µm holes can make use of laser machining/drilling for holes of various depths, depending on the optics and power used. This exceeds the minimum hole diameters that are easily achievable using AM at depths greater than a few mm in many materials and is a significant potential advantage of subtractive manufacturing (SM). CNC methods are common in SM, and at small sizes (< 1mm) are sometimes referred to as micromachining, and here accuracies below 10 µm have been reported [18]. Operation is typically in three cartesian axes, although more advanced systems can use five axes to allow additional rotation and tilting. This approach has perhaps been under-utilised for the fabrication of acoustic metamaterial structures, especially those with metallic substrates; perhaps designs based on manufacturability by five-axis CNC machining could be more thoroughly investigated in future.

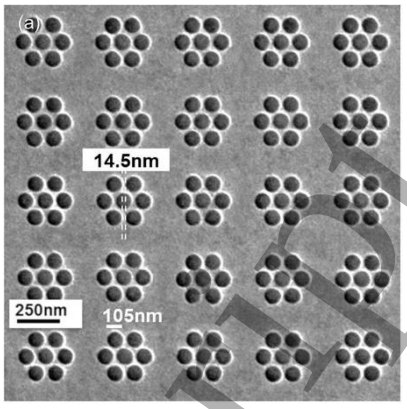


Figure 1. A device with ~100 nm diameter holes in a 100 nm thick gold film made using FIB machining (taken from [11]).

EDM is a technique which is especially useful for electrically conducting materials and harder metals that are difficult to machine conventionally [19]. These are often the same materials that are difficult to fabricate using AM (e.g via techniques such as selective laser melting). The limits of the technique seem to arise from the interaction of the electrical discharge with the part, which is specific to each material [20]. Sinker EDM is used for conductive workpieces and is used where intricate shapes are needed. It's suitability for use with metals was demonstrated via the construction of a broadband acoustic cloaking device in water containing over 500 individual cells within an aluminium structure [21]. Wire EDM is used to cut materials using a thin wire electrode and can be used on hardened steel and titanium alloy surfaces, especially to produce contours. EDM drilling can also be used to drill holes in difficult materials, and its operation is shown in figure 2. These might be particularly useful for the construction of resonant/Fabry-Perot acoustic metamaterial designs.

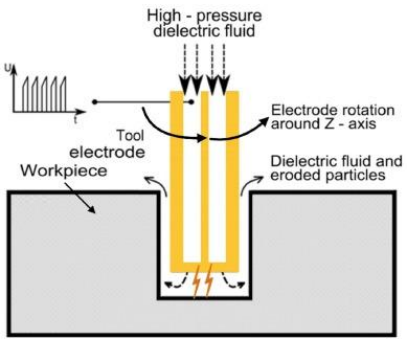


Figure 2. Operation of EDM drilling in a metallic substrate (taken from [20]).

There are various forms of etching used to fabricate features at surfaces. Conventional chemical etching (either isotropic or anisotropic) is widely used in silicon and other semiconductors, with resolutions typically in the µm range. The use of metal assisted chemical etching also introduces greater flexibility [22], including deeper depths of features [23], which could aid in high frequency acoustic metamaterial fabrication. Reactive ion etching (RIE) has been used for example to manufacture a sound absorbing metamaterial panel for use on a gyroscope structure [24]. Here an array of holes was machined into a set of silicon wafers (see figure 3).

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The use of focussed ion beam (FIB) machining can be used to obtain even greater resolutions of up to 5 nm ([11], see figure 1). It is used for the creation of magnetic, optical and THZ metamaterials (e.g. [25]), but is not widely used at present for acoustic devices. This is because of the much shorter wavelengths used in e.g. THz applications.

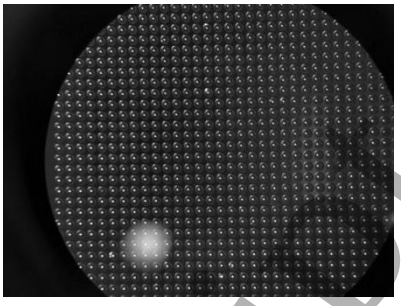


Figure 3. Holes etched into a 4-inch silicon wafer as part of a sound absorbing metamaterial (taken from [24]).

Current and Future Challenges

Acoustic metamaterials (AMMs) and phononic crystals (PCs) can be grouped into six approximate structural types [26]: (i) spherical particles within a fluid medium; (ii) Helmholtz resonators; (iii) Membrane-type structure with or without an added mass; (iv) Lattice arrays of pillars on a plate; (v) Labyrinthine/space-coiling structures and (vi) deformable origami-based surfaces. SM processes are typically used on plates, metasurfaces and metamaterial waveguides, but they are easily adaptable for (ii), (iii), (iv) and (vi). Metamaterial types (i) and (v) are likely to be a more difficult problem. An example of (iv) is Daunzieu *et al.* [27], who constructed a 3D PC metamaterial in aluminium for use at ~60 kHz for friction studies. A metallic plate, machined out of a single aluminium block, had 1.5 mm diameter circular pillars arranged perpendicularly on one surface. AM techniques were avoided due to perceived internal defects and surface roughness issues which are far less significant in SM, a feature that has perhaps been overlooked to date.

The reactive ion etching mentioned above could be used for both AMM and PC fabrication. These processes can be isotropic or anisotropic, e.g. to produce arrays of Helmholtz resonators in silicon wafers with µm resolutions [24]. These arrays are very useful as metamaterial structures for acoustic insulation across a wide frequency range. Such etching techniques also led to the creation of a metamaterial lens operating at 1 MHz using 2 mm thick steel material [28], and they can also be used to create PC graded-index (GRIN) acoustic lenses using a quartz substrate [29]. Etching in silicon and the addition of silicon nitride membranes can be used to fabricate capacitive micromachined ultrasonic transducers (cMUTs [30], see figure 4) which are arrays of individual resonators to which masses can be added (effectively a subtractive/additive hybrid approach). In the form of arrays, these could create metamaterials at silicon surfaces e.g. for energy harvesting or as arrays for improved biomedical ultrasound imaging resolutions as Fabry-Pérot (FP) resonators. The creation of these structures using additive techniques would be very difficult, due to the need for high build resolution in materials that do not lend themselves to AM fabrication routes (i.e. for glasses, hard crystalline materials and semiconductors such as silicon).

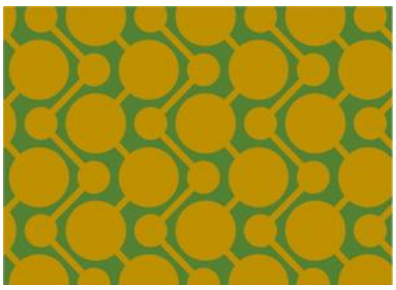


Figure 4: A cMUT showing arrays of membranes of two different sizes on a silicon substrate (taken from [30]).

There are other techniques worth considering. Wire EDM is a manufacturing technique that is increasingly being used in the aerospace industry, but which has not seen much adoption in metamaterial fabrication. It could be useful where very fine tolerances are needed at high acoustic frequencies. It can be used in materials where conventional techniques could be difficult, an example being carbon fibre reinforced composites (CFRPs) [31]. While AM can be used to make CFRP components [32], the use of subtractive techniques such as EDM could be very useful in adding the

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fine detail often needed for acoustic metamaterial operation. It has also been shown that conventional drilling can be used to produce photonic crystals [33], but these could be easily adapted to phononic crystals which could then exhibit bandgaps. This is especially the case for thicker materials where cylindrical channels need to be formed. These acoustic PCs could be used for vibration isolation and the blocking of fundamental ultrasound frequencies in sub-harmonic ultrasound imaging. Electropolishing is a technology that could also be harnessed and has been used for dielectric materials in a SM/AM hybrid approach [34] to form 3D structures in metals. This could also easily be adaptable to metal-based PCs and other metamaterial structures. Table 1 shows the various methods described above, and their respective features.

Table 1: Illustration of the various subtractive manufacturing approaches and their characteristics

Main methods of fabrication	Types of relevant material	Build resolution	Maximum depth or thickness of use	Metamaterial classification
Laser Machining	Metals, Polymers, Ceramics	Kerf 0.1-1mm Features >~1mm	~10mm	ii, vi [35]
Water Jet Machining	Metals, Polymers, Ceramics	Kerf 0.1-2mm Features >~3mm	~20mm	ii, vi
Computer Numeric Control milling	Metals, Polymers, Ceramics	10µm–10mm	Proportional to resolution	ii, iii, iv
Focussed Ion Beam machining	Silicon, Ceramics, Metal films	Features >5nm	<~100µm	ii, iv,
Electric Discharge Machining	Conductive materials	Diameter 0.3-3mm, Aspect ratio <~200 diameters	Up to ~500mm but equipment and diameter dependent	ii, iii, iv,
Chemical Etching	Metals, Silicon, Oxides	Features >~75µm	5µm-2mm	iii, iv, vi
Reactive Ion Etching	Metals, Silicon, Oxides, Semiconductors	Feature size 30nm-100µm, aspect ratio up to 100	1-500µm	iii, iv, vi [36]

There are some key challenges that could limit the use of subtractive manufacturing for acoustic metamaterials. The first of these is limitations in the actual process itself, in that it is difficult to use in metamaterial structures that have different forms of complexity (although some etching techniques could in principle do some simple structures). SM methods such as milling, drilling, laser machining and water jetting effectively act in a linear or planar geometry. Some acoustic metamaterials such as phononic crystals could not easily be fabricated using subtractive methods. The same is true for metamaterial designs with tortuous paths. Increasingly, other techniques such as AM are needed to fabricate such structures and seem to be increasingly dominant in the literature. In terms of applicability to different materials, SM techniques would dominate in simple metallic structures, but the geometric limitations remain (noting that AM methods for metallic substrates could not provide the same level of surface finish).

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SM has an advantage in materials where AM methods cannot easily be used, examples being semiconductors, ceramics and glasses. Here focussed ion beam machining, electric discharge machining, chemical etching and reactive ion etching are of interest. In addition, their resolution is often far better than AM methods. However, SM is more difficult to use in softer solids such as gels, foams etc.

Advances in Science and Technology to Meet Challenges

From the above, it will be seen that SM methods seem to have not received as much attention as they perhaps deserve. It is evident that the use of some subtractive techniques could lead to resolution and surface finishes that would exceed those achievable with AM. The problem in some cases is the depth of penetration. However, this could be overcome by layering pre-fabricated thin structures. After all, AM uses this layering approach. This would suit FP metamaterials allowing changing shapes with depth for polymer/gel substrates and could even lead to possible fabrication of space coiling and colloidal-type structures ((i) and (v) above). Laminations would hinder sound transmission, which is desirable in some FP designs (propagation would be through the holes in this case). For uses where transmission through the substrate is required, suitable joining technologies could be identified to minimise reflections at interfaces. Note that such structures could also use the hole geometry as moulds for 3D PCs. One of the problems encountered with AM methods include surface roughness, particularly in features such as deep holey structures, and where large areas need to be covered. This is where some SM methods, perhaps combined with subsequent layering, might play a part.

Concluding Remarks

The advantages of subtractive manufacturing could well outweigh the difficulties, provided new approaches are considered. Fabrication is generally faster than AM, and in many cases a better surface finish and build resolution is possible. They can be used with a significantly wider range of substrate materials than AM (including semiconductors, fibre-reinforced composites, glasses etc) and are useful if high resolution structures for higher frequency operation are needed. Challenges in implementation for 3D structures exist, but these could be potentially overcome with hybrid approaches using SM with AM, and also by using layering techniques.

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12. Sustainability of metamaterial manufacturing

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Status

A wide variety of manufacturing approaches are employed in metamaterial fabrication, with approach selected according to desired metamaterial application/functionality, length scale, and base material, with specific additive, subtractive and formative approaches outlined in other sections of this roadmap. As outlined in [1], manufacturing techniques and material selection must suit the intended use, with consideration to sustainability and environmental impacts of the metamaterial and its manufacturing. There are many facets of manufacturing sustainability – akin to the 'green' engineering principles [2] – including, but not limited to, resource efficiency, energy intensity, raw material availability, in addition to downstream considerations including durability and end-of-life. The sustainability factors considered in this roadmap are summarised in **Figure 1.** Many intrinsic features to metamaterials, such as geometry-driven functionality, digital design workflows, and the growing use of additive and hybrid manufacturing, already align with resource-efficient and flexible production.

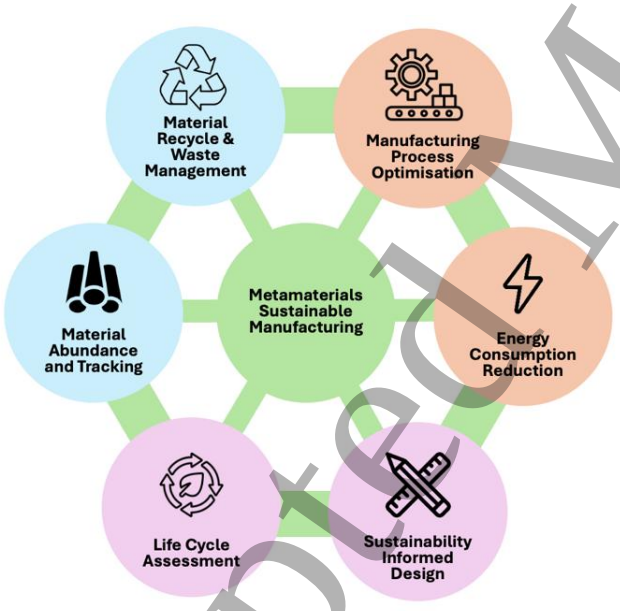


Figure 1: Schematic of considerations relevant to sustainable manufacturing of metamaterials

Additive, subtractive, and formative manufacturing approaches are considered at length within other sections of this roadmap. In **Table 1,** we summarise how the three routes currently compare across several sustainability-relevant dimensions, drawing on analogous studies of metal and polymer component manufacturing. Taken together, these comparisons show that no single process family is unambiguously the most sustainable: the preferred route depends on production volume, part geometry, energy source, and the relative priority given to material efficiency versus end-of-life flexibility. This reinforces the need for context-specific sustainability assessment, rather than generic

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process rankings, when selecting a metamaterial manufacturing route [3-6].

Table 1: Summary of sustainability considerations for current metamaterial manufacturing by additive, subtractive, and formative approaches

	Additive	**Subtractive**	**Formative**
Environmental impacts	• Strongly energy- and feedstock-dependent; impact falls sharply with renewable electricity and topology optimisation [3], but powder/ feedstock production is energy-intensive. • LCA corroborates this process-dependence, with indications that deposition can account for >75% of environmental impacts [4].	• Generally the highest impact route, driven by initial billet size and the volume of material removed due to inherently subtractive nature [3].	• Often the lowest-impact route at production scale once tooling is amortised; casting has been reported the most environmentally favourable option for large runs [3].
Scale up pathways	• Scale-up *via* parallelised/multi-laser systems; most readily justified for low-volume, high-complexity, customised or remanufactured/ repaired parts. • Energy intensity per-part reduces with improved machine utilisation.	• Industrially well-established scale-up; waste and energy burden scale roughly with volume of material removed. • Material waste and energy per-part scales linearly with production volume.	• Mature, high-throughput infrastructure already suited to mass production, but requires high up-front tooling investment. • Per-part energy and waste decrease steeply once volume scales beyond the FM/AM breakeven point depending on process, geometry and material.
End of life	• Potential to reclaim and reuse end-of-life metamaterials as feedstocks for new fabrication and for repair/remanufacture *e.g.,* [7], though repeated powder reuse needs quality control.	• Swarf/chips are recyclable in principle, but contamination from cutting fluids or mixed-material assemblies can complicate reuse.	• Scrap and offcuts (e.g. stamping or forging flash) form well-established, readily remelted recycling streams.

Current and Future Challenges

Sustainability is a key consideration in the manufacture and adoption of metamaterials. Metamaterials offer several advantages in terms of sustainability, as outlined later in this document, but sustainability impacts and considerations appear under-discussed in the literature. Indeed, of the ~500,000 Google

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Scholar results (as of 26/01/2026) referring to metamaterial(s), less than 10% (~40,300) of these results also refer to “sustainable” or “sustainability”. Consequently, when considering this topic, we often turn to wider literature on analogous manufacturing of other materials, to infer the sustainability considerations and impacts relevant to metamaterial fabrication.

Sustainability in metamaterial fabrication starts from base material selection, including the availability and abundance of starting materials. Examples of mechanical, acoustic, electromagnetic and photonic metamaterials highlighted elsewhere in this roadmap have been fabricated from a wide range of base materials, some of which are recognised as ‘critical’ minerals/materials (CRMs) for the UK (e.g., titanium, tellurium, aluminium, silicon), either due to abundance concerns, domestic economic vulnerability and global supply chain risks [8]. Though current metamaterial manufacturing requires relatively low quantities of scarce/critical materials relative to other sectors, scaling-up metamaterials production could increase demand for scarce or critical base-materials, hence steering metamaterial production towards non-critical starting materials has been recommended [9]. However, metamaterials can also offer sustainable alternatives that reduce reliance on other CRMs, by replacing or substituting high-cost, high-value materials with metamaterials [1, 10] or by reducing material consumption through optimizing material geometry [11].

To reduce reliance on raw material extraction, metamaterial fabrication can utilise recycled material, either wholly (*i.e.,* closed loop recycling) or to supplement virgin material. In doing so, it is important to consider that some manufacturing processes are more tolerant than others to recycled feedstocks. For example, thermoplastic materials used in fused deposition modelling or selective laser sintering can be reclaimed and reused. Minimising raw material reliance has been demonstrated for several different aspects of metamaterial manufacturing, *i.e.,* in recovery and reuse of polymeric mechanical metamaterials, where the metamaterial could be recycled several times whilst retaining its shape memory functionality, [7] or in chemical-based subtractive processes, *e.g.*, photolithography or laser patterning/writing employing inks, where solvent/ink recovery, recycling and reuse has been used to minimise financial and environmental impacts of the fabrication process [12]. However, processes can behave unpredictably when using recycled materials, *e.g.*, for AM due to oxidation/contamination of the recycled powders over time, requiring supplementing with virgin material [13]. Establishing standard practices for handling recycled powders or polymers and quality control is essential.

Resource efficiency, in terms of material usage and waste, can differ for different manufacturing methods, *i.e.*, additive (AM), subtractive (SM) and formative (FM). Material efficiency in manufacturing, often referred to as a “buy-to-fly" (BTF) ratio, considers the mass of raw material *vs* that of the finished part. Though such ratios for metamaterials manufacturing have not yet been compared systematically in the literature, analogous BTF studies in metal manufacturing for aerospace and other high-value, high-machining-allowance components provide a useful benchmark and methodological template as a comparison [3]. In general, SM tends to have the highest BTF as removing large volumes of material is required due to the complex geometries of metamaterials; for highly machined parts, BTFs of 10:1 to 20:1 are commonly cited, with values up to 40:1 reported for very geometry-intensive components [14]. FM (e.g., stamping, extrusion, moulding, casting/forging followed by finish machining) typically reduces waste by delivering a near-net preform, giving mid-range BTF ranging from 2:1 to 10:1 [15], depending on how close the preform is to net shape and the finishing allowance required. BTF for AM can approach near-net material usage, with BTF potentially below 3:1 [16] but the realised utilisation is reduced by supports/sacrificial structures, powder or feedstock handling losses, post-machining stock, and failed builds.

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One way to capture the environmental impact of a manufacturing process is through life cycle assessment (LCA). Some manufactured metamaterials have undergone LCA (e.g., AM of thermal metamaterials [14] coatings for photonic 'meta-concrete' [4] and injection moulding of structural metamaterials [18]) but such LCAs are not commonplace. In Google Scholar, of the ~500,000 results (as of 26/01/2026) corresponding to metamaterial(s), just 1,340 also refer to "life cycle assessment". In the absence of widespread metamaterial manufacturing LCAs, understanding environmental impacts could be guided based on assessments of these manufacturing processes such as comparing the environmental impact of additive, subtractive, and formative manufacturing of metals [3]. Such LCA studies have demonstrated that a considerable source of environmental impact comes from the energy/electricity usage of the manufacturing process, with the energy mix used in a specific manufacturing scenario influencing the most suitable – purely from an environmental impact perspective – manufacturing technology [3]. Additionally, closely related work on AM-fabricated lattice/architected structures – geometries themselves a class of mechanical metamaterial – indicates that mass savings do not guarantee lower environmental impact: longer build times and auxiliary equipment use can outweigh material savings [19], with outcomes also sensitive to unit-cell size [20]. Considering AM and thin film deposition/coating as exemplars of manufacturing approaches relevant to metamaterials, LCA studies have identified key areas with potential to reduce future environmental impacts in optimising reactor/equipment design to minimise waste and emissions, improving throughput to lower the overall energy budget for a specific process, and designing greener precursors/feedstocks and AM support structures [21, 22].

Based on impact assessments conducted for other materials, several sustainability considerations, applicable to metamaterial manufacturing, emerge. One such recommendation is to not consider the choice of manufacturing technique in isolation, but also to consider base material selection and design changes resulting from changing and scaling up manufacturing processes [23]. Additionally, machine (under)utilization can have a considerable environmental impact, whereby the embodied energy per manufactured unit can be reduced by an order of magnitude by improving machine utilisation [24], a factor particularly relevant to fabrication of highly specialised metamaterials, where few specimens may be required at a time.

At present, much metamaterials manufacturing activity remains at laboratory to pilot scale (typically lower technology and manufacturing readiness levels), reflecting the research-intensive nature of the field, and changes in environmental impact/sustainability should be captured during the scale up process. Sustainability studies focusing on nanofabrication techniques, many of which are directly applicable to metamaterial manufacturing, recommend early-stage incorporation of LCAs [25] to ensure such technologies are scaled-up sustainably. As metamaterials and fabrication processes progress through the technology readiness and scale-up levels, environmental and life cycle impacts may differ. Although sparse primary data for scaled-up manufacturing poses challenges, LCA methodologies can estimate industrial environmental impacts from laboratory-scale data [26], which may help inform decision making regarding suitable manufacturing approaches for scale-up.

With increasing production and adoption of metamaterials, metamaterial-containing devices will inevitably reach the end of their operational life, and be retired, either for replacement, repair, or reuse or recycling. Sustainability and end-of-life considerations for a given metamaterial may be driven by the end application/context of the metamaterial, *e.g.*, for large length scale metamaterials, such as acoustic metamaterials which may be incorporated in construction, sector-specific guidance may be applicable, *e.g.* materials/product passports to enable material reuse at end-of-life [27]. Current examples of how metamaterial end-of-life is addressed include disassemblable and reconfigurable

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mechanical metamaterials [28] for extended operational lifespan [29], or recycling of polymeric metamaterials by chemically etching [7] or melting [30] with subsequent re-manufacture by AM. Multi-material or composite materials may be more challenging to recover and recycle [9], hence reduced material diversity [2] within a system could be advantageous come end-of-life. Many existing LCAs of metamaterial fabrication set their scope as gate-to-gate [17] or cradle-to-gate [4, 18], but expanding scopes to consider cradle-to-grave or cradle-to-cradle would enable end-of-life management impacts to also be captured.

Advances in Science and Technology to Meet Challenges

- Design method and modelling: A key advance lies in the increasing integration of sustainability considerations at the design stage [31]. Computational design, topology optimisation, and inverse design methods now allow metamaterial architectures to be tailored not only for performance but also for manufacturability, robustness, and material efficiency. By incorporating fabrication constraints and tolerance analysis into early-stage design, these approaches reduce sensitivity to defects, improve yield, and limit iterative prototyping. Digital twins and simulation-driven workflows further support efficient process development, reducing material consumption and energy use during experimentation [32].
- Assessment tools and early-stage metrics: growing adoption of sustainability assessment tools is enabling more informed decision-making [33]. Evolved life-cycle assessment methods, including material criticality analysis and process-level energy accounting, provide an important link between laboratory-scale innovation and industrial sustainability requirements. When applied at early development stages, these tools support proactive evaluation of trade-offs between performance, manufacturability, and sustainability.
- End-of-life management: In more mature industries, such as metals or polymers, recent increases in material and chemical complexity now pose challenges and potential barriers to straightforward end-of-life management e.g., recycling [34, 35]. Consequently, strategies to reduce chemical and material complexity whilst maintaining performance are desirable – a challenge perhaps well-suited to metamaterials, with many examples of metamaterials made from single material systems [36, 37]. It is important to consider the downstream implications when designing metamaterials, with reduced material complexity in manufacturing also advantageous at end of life.

Concluding Remarks

Sustainability will play an increasingly important role in shaping the future of metamaterials manufacturing as the field moves from laboratory demonstration toward scalable deployment. While early research has focused primarily on achieving novel and high-performance functionalities, current manufacturing capabilities now allow sustainability considerations to be addressed in a more systematic and proactive manner. By treating sustainability as an enabling factor rather than a limitation, the metamaterials community can support resilient supply chains, reduced environmental impact, and alignment with broader manufacturing and policy priorities. In doing so, sustainable manufacturing will become a key contributor to the long-term technological and societal impact of metamaterials.

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