Scripta Materialia xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Scripta Materialia

journal homepage: www.elsevier.com/locate/scriptamat

Viewpoint Article

Additive manufacturing: Toward holistic design

Bradley H. Jared *, Miguel A. Aguilo, Lauren L. Beghini, Brad L. Boyce, Brett W. Clark, Adam Cook, Bryan J. Kaehr, Joshua Robbins

Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185, USA

ARTICLE INFO

Article history:
Received 3 August 2016
Received in revised form 10 February 2017
Accepted 19 February 2017
Available online xxxx

Keywords:
Additive manufacturing
Solid freeform processes
Simulation
Modeling
Analytical methods

ABSTRACT

Additive manufacturing offers unprecedented opportunities to design complex structures optimized for performance envelopes inaccessible under conventional manufacturing constraints. Additive processes also promote realization of engineered materials with microstructures and properties that are impossible via traditional synthesis techniques. Enthused by these capabilities, optimization design tools have experienced a recent revival. The current capabilities of additive processes and optimization tools are summarized briefly, while an emerging opportunity is discussed to achieve a holistic design paradigm whereby computational tools are integrated with stochastic process and material awareness to enable the concurrent optimization of design topologies, material constructs and fabrication processes.

1. Motivation

Additive manufacturing (AM) is leading a renaissance in global manufacturing and product development spurred in part by claims that "complexity is free" [1,2]. AM offers prospects to design complex geometries that can be optimized for performance gains inaccessible under conventional manufacturing constraints. AM further introduces the potential to generate complex, engineered materials with composition gradients, microstructures and properties that are impossible via traditional synthesis techniques. In a similar, synergistic trajectory, topology optimization (TO) is receiving growing attention and use by engineers who seek advanced design tools to leverage the full capabilities of AM materials and processes. Seminal work from both fields emerged in the late 1980s [3,4,5], but research and development activities remained in isolation with earliest references to integration occurring near the turn of the millennium [6,7]. Recent activity is reversing this trend as researchers, engineers and even consumers across a range of applications and disciplines are coupling TO with AM to satisfy growing appetites for robust products, design freedom and high yield production. However, before complexity becomes truly free, or at least significantly cheaper, capability gaps and challenges in materials, processes and optimization tools must be addressed. The discussion that follows will identify key challenges and discuss intersections across the additive and optimization communities where research and technology maturation is necessary to realize a holistic design paradigm that intimately couples design optimization with process and material capabilities.

2. State-of-the-art

2.1. Additive processes and materials

At their core, additive processes generate material and geometry concurrently as material is deposited, typically in a layerwise fashion, to fabricate three-dimensional parts from solid model representations [8]. As a result, AM introduces the unique possibility to generate and locally control geometry and material at every volume element, i.e. "voxel", in a part. Complex freeform geometries, internal and reentrant features, architectured materials, and multi-functional, multi-material parts all become realizable and enter the design space within the additive paradigm. ASTM currently recognizes seven additive process categories; vat photo-polymerization, material extrusion, material jetting, binder jetting, powder bed fusion, directed energy deposition, and sheet lamination [8]. Since process descriptions and details are available through a multitude of sources [9,10,11], general capabilities relative to geometric and material complexity are highlighted.

Geometric complexity is inherently available in every additive technique. Polymer based methods are considered the most mature and capable as they represent the earliest additive processes [3,4]. Vat photopolymerization, i.e. stereolithography, and material jetting leverage photopolymer material systems, enable almost arbitrary geometry forms, and provide the best surface finish, part accuracy and feature resolution among processes [4,12,13]. Material extrusion and powder bed

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* Corresponding author at: Sandia National Laboratories, PO Box 5800, MS 0958, Albuquerque, NM 81785, USA.
E-mail address: bhjared@sandia.gov (B.H. Jared).

http://dx.doi.org/10.1016/j.scriptamat.2017.02.029

Please cite this article as: B.H. Jared, et al., Additive manufacturing: Toward holistic design, Scripta Materialia (2017), http://dx.doi.org/10.1016/j.scriptamat.2017.02.029

fusion, i.e. selective laser sintering, process a much wider range of thermoplastic materials, including those with fillers [14,15], but are restricted relative to overhang geometries, surface finish and feature resolution [13,16]. Powder bed techniques, i.e. powder bed fusion and binder jetting, are most commonly used to fabricate complex metal part geometries [17,18]. A range of metal alloys are printable as feature resolution is sub-1 mm, overhang slopes are limited to roughly 45°, and form accuracy and surface finish are competitive with castings. Directed energy deposition processes a similar range of alloys, but provides higher deposition rates for larger parts, courser features and rougher surfaces that restrict its use for complex structures [17]. Sheet lamination is available for ultrasonically weldable materials where layer thickness and in-process machining capabilities limit part geometry [19]. Material jetting represents an exciting, alternative technology with great promise for geometric complexity. It is traditionally associated with low melting temperature metals such as solders [20], but represents an active research area for a larger alloy range with recent promises for commercial equipment [21,22,23]. While additive processes for ceramics lag polymers and metals, binder jetting has been successful for rapid prototyping due to its ability to produce complex, full color geometries, albeit with poor surface finish and weak materials [24,25]. More recently accessible and useful materials include sand [26], glass and tungsten carbide [18]. Material extrusion is a common process route for ceramics due to its scalability and compatibility with traditional processing routes. Geometry, however, is limited by nozzle shape and feedstock rheology [27,28]. Overhang features are generally inaccessible and surface morphology is dominated by extrusion patterns. Vat photo-polymerization represents a new technology for ceramics that is advancing rapidly and shows great potential for complex parts with feature resolutions below 100 μm [29,30].

While geometric freedom is a classic motivation for additively manufactured components, emerging applications are increasingly driven by an unprecedented ability to access material complexity that is now available in three forms. *Architected materials*, ex. metamaterials or lattices, leverage the geometrical complexity and scaling afforded by AM to create sub-part scale structures that produce effective material properties distinct from fully dense monoliths. Architected materials are primarily of single material constructions and have been used for negative stiffness [31], light-weighting [32], and flexible electronics [33]. Fig. 1 shows one such example, a lattice structure designed to solve the 3D Mitchell beam problem [34]. The loading configuration consists of a vertical load on the center of the right face and a fixed displacement on the left face. Homogenized elastic constants are computed for a 20% dense octahedral lattice unit cell and then used in computation of the optimized topology. A conformal hexahedral mesh is computed and applied to the resultant topology. The octahedral unit structure is then mapped into each hexahedron to arrive at the final part geometry. The structure provides a stiffness that is roughly 70% greater than a fully dense part with identical mass. A 38 mm tall version of the structure was fabricated in 316L stainless steel using laser powder bed fusion, while multi-photon lithography was used to print a 500 μm tall version of the part in IP-S photosensitive resist. *Microstructure control* is common in any material formation process, but only additive techniques enable control at discrete voxels through a part volume. Process maps have quantified ranges for microstructure control in additive processes for over a decade [35,36]. Researchers have also used electron beam melting to change the crystallographic texture of grains in Inconel 718 to produce coarse columnar grains, epitaxial deposits and fully equiaxed grains through precise control of process parameters [37], Fig. 2. Such work highlights the ability to generate local microstructures and hence material properties by controlled manipulation of process inputs to accommodate the complex stress state in a part. *Multi-material* parts contain diverse material compositions within a single geometry, often with multi-functional capability. Polymer processes are most mature as locally varying material properties [38,39,40], color [38,39,40,41,42,43] and material gradients [8,14,15] have been demonstrated using commercial machines [38,39,40,41]. Directed energy deposition provides access to gradient metals through OEM systems [44,45], while powder bed techniques have been demonstrated but not commercialized for multi-material parts [46,47,48]. Sheet lamination provides access to gradient materials and the unique integration of embedded electronics and sensors [19]. Techniques for printing across material types (i.e. polymer, metal, ceramic) are limited, but extremely compelling and are poised to enable an even wider design space. Direct write material extrusion has generated parts with embedded electrical capabilities [49,50], while material jetting has produced opto-electronic devices with printed optics and drop-in electrical components [12].

2.2. Design optimization

Generally, the topology optimization problem involves finding the spatial distribution of material attributes that optimizes a performance objective for a design domain and set of requirements. In its simplest form, it is an iterative procedure. First, the response to a candidate design is computed as fields satisfying the state equations are determined for the current design and then used as the basis for evaluation of the performance objective and its sensitivity to change. Field solutions can be found using well-established analysis codes such as Abaqus™ [51], Nastran™ [52], Sierra Mechanics [53], or Albany [54]. Design changes are then determined as the objective, sensitivity, and other information from the performance calculation are passed to an optimization engine that updates the design while enforcing constraints and performance requirements. Basic iteration continues until convergence to an optimal design with respect to functional requirements is met or iteration limits are exceeded. Optimization based design has become an increasingly active and diverse field of research as multiple techniques and tools are now available [55,56,57]. Research codes are readily accessible, but provide limited capabilities and are not properly supported to address user needs [58,59]. Commercial software is more user friendly and can deliver size, shape, bead, topography, topometry and freeform optimization methodologies to complement topology based calculations [60,61,62]. Minimization of compliance is a common structural problem

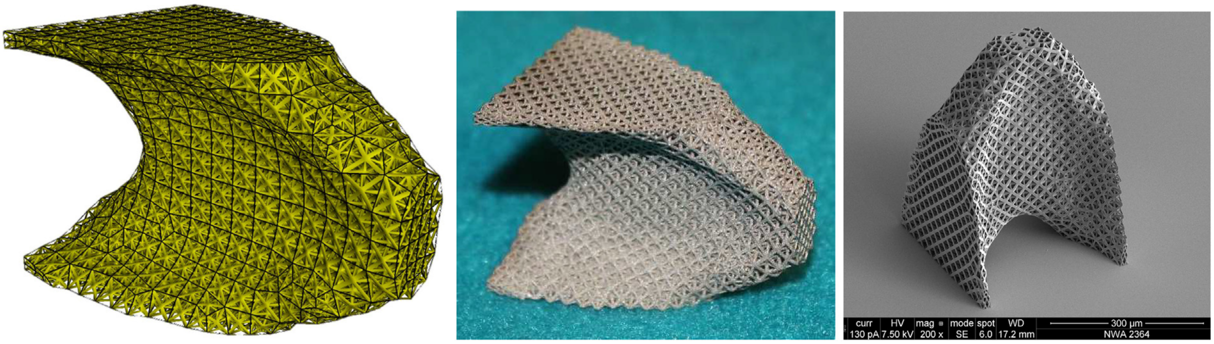

Fig. 1. A 3D Mitchell structure (left) designed with tetrahedron lattices [34] that was fabricated using laser powder bed fusion (center) and multi-photon lithography (right).

Please cite this article as: B.H. Jared, et al., Additive manufacturing: Toward holistic design, Scripta Materialia (2017), http://dx.doi.org/10.1016/j.scriptamat.2017.02.029