WHAT ARE PRINCIPLES FOR DESIGN FOR ADDITIVE MANUFACTURING?

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ABSTRACT: Additive Manufacturing (AM) technologies enable the fabrication of parts and devices that are geometrically complex, have graded material compositions, and can be customized. To take advantage of these capabilities, it is important to guide engineering designers through the various issues that are unique to AM. We explore the range of principles that are relevant to Design for Additive Manufacturing (DFAM) in this paper. These include ideas about generating designs that cannot be fabricated using conventional methods to understanding the realities of existing machines and materials to micro-scale issues related to material microstructures and resulting process variations. Comments about standardization efforts in the ASTM and ISO organizations are also included.

INTRODUCTION

Traditionally, Design For Manufacturing (DFM) has meant that designers should tailor their designs to eliminate manufacturing difficulties and minimize costs. However, the emergence of Additive Manufacturing (AM) technologies provides an opportunity to re-think DFM to take advantage of the unique capabilities of these technologies. In contrast to DFM, we believe the objective of Design For Additive Manufacturing should be to:

> Maximize product performance through the synthesis of shapes, sizes, hierarchical structures, and material compositions, subject to the capabilities of AM technologies.

AM differs from other manufacturing processes for several reasons and these differences lead to unique design opportunities and freedoms that are highlighted here (Gibson et al., 2010). As a general rule, if a part can be fabricated economically using a conventional manufacturing process, that part should probably not be produced using AM. Instead, parts that are good candidates for AM tend to have complex geometries, custom geometries, low production volumes, special combinations of properties or characteristics, or some combination of these characteristics. Several companies are now using AM technologies for production manufacturing. For example, Siemens, Phonak, Widex, and the other hearing aid manufacturers use powder bed fusion (PBF) (selective laser sintering) and vat polymerization machines to produce hearing aid shells, several European companies are fabricating thousands of hip implant components using metal powder bed fusion machines, and Boeing and its suppliers use PBF to produce ducts and similar parts for F-18 fighter jets. In the first three cases, AM machines enable one-off, custom manufacturing of 10's to 100's of thousands of parts. In the last case, AM technology enables low volume manufacturing and, at least as importantly, piece part reductions to greatly simplify product assembly.

An overview of design principles and AM unique characteristics are offered next. Then, the principles and characteristics are illustrated with topics on novel design strategies, design for production considerations, functionally graded components, and standards for design guidelines.

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OVERALL PRINCIPLES AND UNIQUENESS

In AM processes, parts are fabricated by adding material in a layer-by-layer manner. Due to their nature, AM has many more degrees of freedom than other manufacturing processes. For example, a part may be composed of millions of droplets if fabricated in a material jetting process. Discrete control over millions of operations at micro to nano scales is both an opportunity and a challenge. Unprecedented levels of interdependence are evident among considerations and manufacturing process variables, which distinguishes AM from conventional manufacturing processes.

More generally, the unique capabilities of AM technologies enable new opportunities for customization, improvements in product performance, multi-functionality, and lower overall manufacturing costs. These unique capabilities include:

- **Shape complexity:** it is possible to build virtually any shape, lot sizes of one are practical, customized geometries are achieved readily, and shape optimization is enabled.
- **Material complexity:** material can be processed one point, or one layer, at a time, enabling the manufacture of parts with complex material compositions and designed property gradients.
- **Hierarchical complexity:** this refers to the multi-scale of features, sub-features, etc. that are possible with AM.
- **Functional complexity:** Functional devices can be fabricated directly in some AM machine, by embedded components and kinematic joints while parts are being built.

AM's layer-based, additive nature means that virtually any part shapes can be fabricated without hard tooling, such as molds, dies, or fixtures. Geometries that are customized to individuals can be fabricated economically. Very sophisticated geometric constructions are possible using cellular structures (honeycombs, lattices, foams) or more general structures. Often, multiple parts that were conventionally manufactured can be replaced with a single part, or smaller number of parts, that is geometrically more complex than the parts being replaced. This can lead to the development of parts that are lighter and perform better than the assemblies they replace. Furthermore, such part count reduction (called part consolidation) has numerous benefits for downstream activities. Assembly time, repair time, shop floor complexity, replacement part inventory, and tooling can be reduced, leading to cost savings throughout the life of the product.

To generalize from the observations and examples, the following DFAM principles can be offered:

- AM enables the usage of complex geometry in achieving design goals without incurring time or cost penalties compared to simple geometry; this allows designers to avoid most manufacturing process constraints;
- AM enables the usage of customized geometry and parts by direct production from 3D data;
- with AM, it is often possible to consolidate parts, integrating features into more complex parts and avoiding assembly issues;
- direct fabrication from digital data and the avoidance of hard tooling enable low production volumes to be economical, in many cases.

NOVEL DESIGN STRATEGIES

Some treatises have been written about AM and its promise; the latest is Lipson's and Kurman's book *Fabricated: The New World of 3D Printing*, which explores many creative ideas about how the technology could be used in the future in industry, homes, schools, and even kitchens, hospitals, and the fashion industry (Lipson & Kurman, 2013). Many insights are provided into the technology and its applications.

In terms of design methods and tools to support DFAM, relatively few papers have been written. The challenge is that new design spaces need to be formulated and explored, requiring significant creativity and innovation to first develop new design concepts and then pursue them into practice. However, some researchers have to formulate a general design method that takes into account product functionality and manufacturing constraints for AM (Ponche et al., 2012). Instead, most researchers and technologists pursue a specific niche in the creative space and develop specific methods and tools for that niche. Three specific areas will be summarized in this section. First, the concept of Design for Functionality can be realized, meaning that if a part's functions can be defined mathematically, the part can be optimized to achieve those functions as well as possible. Novel topology and shape optimization methods have been developed in this regard. Second, the area of cellular structures has seen a lot of interest with both research and commercial tools being developed. Third, the redesign of kinematic mechanisms as compliant mechanisms is another area with significant research accomplishments.

The specific topic of topology optimization, within the design for functionality area, has received a lot of research attention, but not as much emphasis on AM fabrication than is warranted. Broadly speaking, topology optimization is a type of structural optimization where the overall shape, arrangement of shape elements, and connectivity of the design domain are determined (Bendsoe, 1989). Typically, part volume or compliance is minimized, subject to constraints on, for example, volume, compliance, stress, strain energy, and possibly additional considerations. Commercial software systems provide a fairly general topology optimization capability for problems where the structural and system behavior can be simulated by finite element and/or multi-body dynamics analyses. Some initial work has investigated different optimization algorithms and, although preliminary, some impressive results have been achieved (Aremu et al., 2013).

Cellular materials (materials with voids) include foams, honeycombs, and lattice structures, and are representative of approaches that take advantage of AM's geometric complexity capability. From a mechanical engineering viewpoint, a key advantage offered by cellular materials is high strength accompanied by a relatively low mass. These materials can provide good energy absorption characteristics and good thermal and acoustic insulation properties as well (Gibson & Ashby, 1997). In the past 15 years, the area of lattice materials has received considerable attention due to their inherent advantages over foams in providing light, stiff, and strong materials. Some commercial software systems support lattice structure design, e.g., from netFabb, Within Technologies, and Materialise. An example application of lattice structures is for a hand-held unmanned aerial vehicle (UAV) that is shown in Fig. 1. The wings and fuselage were fabricated using powder-bed fusion by a division of 3D Systems, assembled, and flown.

AM can enable creative designs of complex 2D and 3D mechanisms. In contrast to multi-part mechanisms, other types of mechanisms cause relative movement between the input and the output through designed bending patterns. That is, structural elements of the mechanism bend in a manner that causes desired input-output behavior. The simplest types of compliant mechanisms simply replace pin joints with thin plates that act as compliant hinges. More sophisticated compliant mechanisms consist of beams with different widths, and possibly varying thicknesses. One example is shown in Fig. 2, which is a mechanism designed using topology optimization (Meisel et al., 2013). An interesting variation of a compliant mechanism is a deployable structure.

One group developed a topology optimization method for designing deployable structures with lattice-reinforced skins (Namasivayam and Seepersad, 2011). Resulting bridge and aircraft wing designs were fabricated using powder bed fusion and deployed via air inflation.

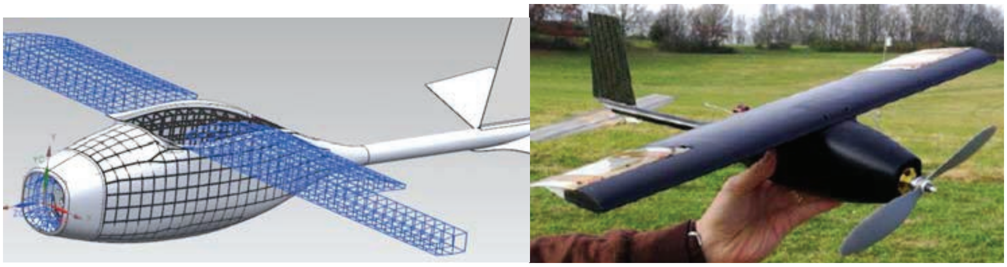
a) b)

Figure 1. Hand-held UAV with conformal lattice structure: a) CAD model and b) ready to fly.

DESIGN FOR PRODUCTION CONSIDERATIONS

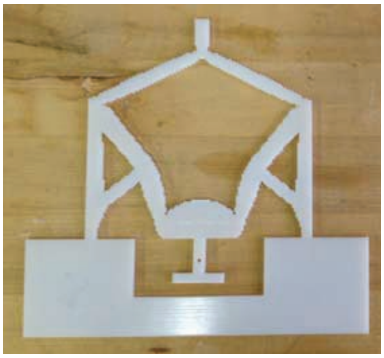
Figure 2. Compliant mechanism.

In this category of methods, we refer to considerations that impact production, including fabrication and assembly issues, similar to traditional DFM practices. Related to design effectiveness, the designer can search for part shapes and configurations that optimize performance and efficiency. Parts can be designed for desired properties, such as minimum weight, maximum stiffness, etc., by designing shapes that are as efficient as possible. It may also be possible to design a part to perform multiple functions (a multi-functional part), through the use of multiple materials, complex shapes or part consolidation, which can have significant efficiency benefits. It is good design practice to minimize the number of parts in a product or module, but not at a loss of functionality. A part may be merged into neighboring part(s) if they: can be fabricated out of the same material as a neighboring part, do not need to move relative to each other, and do not need to be removed to enable access to another part.

Another good, standard DFM practice is to design in ease of assembly. One should design parts with features that enable easy insertion and fixation during assembly operations. AM can enable integration of assembly features into most part designs, such as snap-fits, alignment features, and features to support other parts (ribs, bosses). The capability of AM to fabricate geometrically complex designs provides a greater degree of design flexibility/freedom and designers are encouraged to be innovative in designing assembly features. Some research has investigated the automated design of assembly features, particularly for AM-fabricated parts (Delebecque, 2008).

MULTI-MATERIAL AND MULTI-FUNCTIONAL COMPONENTS

In many AM processes, material compositions or properties can be varied throughout a part. This capability leads to functionally graded parts, in which desired mechanical property distributions can be fabricated by varying either material composition (Shin et al., 2003) or material microstructure (Saheli et al., 2004). If effective mechanical properties are desired to vary throughout a part, the designer can achieve this by taking advantage of the geometric complexity capability of AM processes, such as the lattice structure example earlier. If varying material composition or microstructure is desired, then such variations can be achieved, but with limits given current machine capabilities. For polymer materials, currently only material jetting processes are capable of fabricating parts with material compositions that vary in all directions. In the metals area, only the directed energy deposition process can produce variable material compositions, although all of the metal processes can produce parts with microstructures that vary throughout the part.

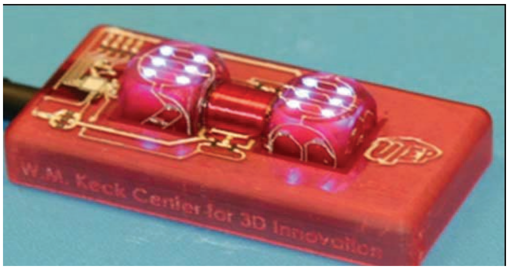

Figure 3. Functional device fabrication using SL and DW.

Multi-functionality can be achieved by unique combination of AM technologies to produce, for instance, 3D integrated electronics. Researchers in the W.M. Keck Center for 3D Innovation at the University of Texas at El Paso have demonstrated the ability to produce a number of working devices by novel combinations of SL and DW (Lopes et al. 2012). Figure 3 illustrates the process plan for fabrication of a magnetic flux sensor using SL and a nozzle-based DW process. Researchers have demonstrated similar capabilities with extrusion-based systems, ultrasonic consolidation, and SLS and other technologies as well.

STANDARDS FOR DESIGN GUIDELINES

Standards for AM are being pursued in a collaboration between two standards organization. In ASTM International, the F-42 committee has efforts on materials and processes, test methods, and design (ASTM). ISO has technical committee TC 261. Both committees are cooperating on a draft standard on design guidelines, the purpose of which is to provide guidelines for designing parts and products to be produced by AM processes. Conditions of the part or product that favor AM are highlighted, as well as conditions that favor conventional manufacturing processes. The main elements of the guide include: the opportunities and design freedoms that AM offers designers, the issues that designers should consider when designing parts for AM, and warnings to designers, or “red flag” issues, that indicate situations that often lead to problems in many AM systems. The main content is a set of design considerations including product development, usage, sustainability, business, geometric, material property, process, and communications considerations. Currently, standards are being developed in the areas of design guides for specific AM processes, starting with powder bed fusion, and a guide for process selection.

Some research groups have proposed technologies or methods that provide foundations for standards. A group at the University of Paderborn developed a set of design rules for powder bed fusion and material extrusion processes (Zimmer & Adam, 2011). More fundamentally, they proposed a set of standard geometric elements and their mathematical definitions that potentially provide a common foundation for design rules across all AM processes.

CLOSURE

AM offers unique fabrication capabilities that engineering designers can exploit. To enable this exploitation, it is important to answer the question of what principles can guide design for AM.

Four over-arching principles were offered, including geometric complexity without cost penalties, customized parts, part consolidation opportunities, and low production volume capabilities. Several unique characteristics of AM were identified, as well. Examples were given that illustrate the application of the principles to a wide variety of engineering areas. Novel design strategies were highlighted, including general design methods, cellular structures, and compliant mechanisms. Topics in the design for production area were described. Finally, applications in multi-material and multi-function design were given. As a concluding statement, most researchers have identified a specific niche in which to develop design methods and tools, rather than attempting to develop an overall, comprehensive DFAM methodology.

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