Design for Additive Manufacturing 17

Abstract

Design for manufacture and assembly (DFM) has typically meant that designers should tailor their designs to eliminate manufacturing difficulties and minimize manufacturing, assembly, and logistics costs. However, the capabilities of additive manufacturing technologies provide an opportunity to rethink DFM to take advantage of the unique capabilities of these technologies. As mentioned in Chap. 16, several companies are now using AM technologies for production manufacturing. For example, Siemens, Phonak, Widex, and the other hearing aid manufacturers use selective laser sintering and stereolithography machines to produce hearing aid shells; Align Technology uses stereolithography to fabricate molds for producing clear dental braces ("aligners"); and Boeing and its suppliers use polymer powder bed fusion (PBF) to produce ducts and similar parts for F-17 fighter jets. For hearing aids and dental aligners, AM machines enable manufacturing of tens to hundreds of thousands of parts, where each part is uniquely customized based upon person-specific geometric data. In the case of aircraft components, AM technology enables low-volume manufacturing, easy integration of design changes and, at least as importantly, piece part reductions to greatly simplify product assembly.

The unique capabilities of AM include: *shape complexity*, in that it is possible to build virtually any shape; *hierarchical complexity*, in that hierarchical multiscale structures can be designed and fabricated from the microstructure through geometric mesostructure (sizes in the millimeter range) to the part-scale macrostructure; *material complexity*, in that material can be processed one point, or one layer, at a time; and *functional complexity*, in that fully functional assemblies and mechanisms can be fabricated directly using AM processes. These unique capabilities enable new opportunities for customization, very significant improvements in product performance, multifunctionality, and lower overall manufacturing costs. These capabilities will be expanded upon in Sects. 17.3 and 17.4.

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17.1 Motivation

Design for manufacture and assembly (DFM[1]) has typically meant that designers should tailor their designs to eliminate manufacturing difficulties and minimize manufacturing, assembly, and logistics costs. However, the capabilities of additive manufacturing technologies provide an opportunity to rethink DFM to take advantage of the unique capabilities of these technologies. As covered in Chap. 16, several companies are now using AM technologies for production manufacturing. For example, Siemens, Phonak, Widex, and the other hearing aid manufacturers use selective laser sintering and stereolithography machines to produce hearing aid shells; Align Technology uses stereolithography to fabricate molds for producing clear dental braces ("aligners"); and Boeing and its suppliers use selective laser sintering to produce ducts and similar parts for F-18 fighter jets. For hearing aids and dental aligners, AM machines enable manufacturing of tens to hundreds of thousands of parts; where each part is uniquely customized based upon person-specific geometric data. In the case of aircraft components, AM technology enables low-volume manufacturing, easy integration of design changes and, at least as importantly, piece part reductions to greatly simplify product assembly.

The unique capabilities of AM technologies enable new opportunities for customization, very significant improvements in product performance, multifunctionality, and lower overall manufacturing costs. These unique capabilities include: *shape complexity*, in that it is possible to build virtually any shape; *hierarchical complexity*, in that hierarchical multiscale structures can be designed and fabricated from the microstructure through geometric mesostructure (sizes in the millimeter range) to the part-scale macrostructure; *material complexity*, in that material can be processed one point, or one layer, at a time; and *functional complexity*, in that fully functional assemblies and mechanisms can be fabricated directly using AM processes. These capabilities will be expanded upon in Sect. 17.3.

In this chapter, we begin with a brief look at DFM to draw contrasts with Design for Additive Manufacturing (DFAM). A considerable part of the chapter is devoted to the unique capabilities of AM technologies and a variety of illustrations of these capabilities. We cover the emerging area of engineered cellular materials and relate it to AM's unique capabilities. Perhaps the most exciting aspect of AM is the design freedom that is enabled; we illustrate this with several examples from the area of industrial design (housewares, consumer products) that exhibit unique approaches to product design, resulting in geometries that can be fabricated only using AM processes. The limitations of current computer-aided design (CAD) tools are discussed, and thoughts on capabilities and technologies needed for DFAM are

[1] Design for manufacturing is typically abbreviated DFM, whereas design for manufacture and assembly is typically abbreviated as DFMA. To avoid confusion with the abbreviation for design for additive manufacturing (DFAM), we have utilized the shorter abbreviation DFM to encompass both design for manufacture and design for assembly.

presented. The chapter concludes with a discussion of design synthesis approaches to optimize designs.

17.2 Design for Manufacturing and Assembly

Design for manufacturing and assembly can be defined as the practice of designing products to reduce, and hopefully minimize, manufacturing and assembly difficulties and costs. This makes perfectly good sense, as why would one want to increase costs? However, DFM requires extensive knowledge of manufacturing and assembly processes, supplier capabilities, material behavior, etc. DFM, although simple conceptually, can be difficult and time consuming to apply. To achieve the objectives of DFM, researchers and companies have developed a large number of methods, tools, and practices. Our purpose in this chapter is not to cover the wide spectrum of DFM advances; rather, it is to convey a sense of the variety of DFM approaches so that we can compare and contrast DFAM with DFM.

Broadly speaking, DFM efforts can be classified into three categories:

- Industry practices, including reorganization of product development using integrated product teams, concurrent engineering, and the like
- Collections of DFM rules and practices
- University research in DFM methods, tools, and environments

During the 1980s and 1990s, much of the product development industry underwent significant changes in structuring product development organizations [1]. Companies such as Boeing, Pratt & Whitney, and Ford reorganized product development into teams of designers, engineers, manufacturing personnel, and possibly other groups; these teams could have hundreds or even thousands of people. The idea was to ensure good communication among the team so that design decisions could be made with adequate information about manufacturing processes, factory floor capabilities, and customer requirements. Concurrently, manufacturing engineers could understand decision rationale and start process planning and tooling development to prepare for the in-progress designs. A significant driver of this restructuring was to identify conflicts early in the product development process and reduce the need for redesign or, even worse, retooling of manufacturing processes after production starts.

The second category of DFM work, that of DFM rules and practices, is best exemplified by the Handbook for Product Design for Manufacture [2]. The 1986 edition of this handbook was over 950 pages long, with detailed descriptions of engineering materials, manufacturing processes, and rules-of-thumb. Extensive examples of good and bad practices are offered for product design for many of these manufacturing processes, such as molding, stamping, casting, forging, machining, and assembly.

University research during the 1980s and 1990s started with the development of tools and metrics for part manufacture and assembly. The Boothroyd and Dewhurst toolkit is probably the most well-known example [3]. The main concept was to develop simple tools for designers to evaluate the manufacturability of their designs. For example, injection molding DFM tools were developed that asked designers to identify how many undercuts were in a part, how much geometric detail is in a part, how many tight tolerances were needed, and similar information. From this information, the tool provided assessments of manufacturability difficulties, costs estimates, and provided some suggestions about part redesign. Similar tools and metrics were developed for many manufacturing and assembly processes, based in part on the Handbook mentioned above, and similar collections of information. Some of these tools and methods were manual, while others were automated; some were integrated into CAD systems and performed automated recognition of difficulties. For instance, Boothroy Dewhurst, Inc. markets a set of software tools that help designers conceive and modify their design to achieve lower-cost parts, taking into account the specific manufacturing process being utilized. In addition, they sell software tools which help designers improve the design of assembled components through identification of the key functional requirements of an assembled component; leading the designer through a process of design modifications with the aim of minimizing the number of parts and assembly operations used to create that assembled component. The work in this area is extensive; see for example, the ASME Journal of Mechanical Design and the ASME International Design Engineering Technical Conferences proceedings since the mid-1980s (see e.g., [4]).

The extensive efforts on DFM over many years are an indication of the difficulty and pervasiveness of the issues surrounding DFM. In effect, DFM is about the designer understanding the constraints imposed by manufacturing processes, then designing products to minimize constraint violation. Some of these difficulties are lessened when parts are manufactured by AM technologies, but some are not. Integrated product development teams that practice concurrent engineering make sense, regardless of intended manufacturing processes. Rules, methods, and tools that assist designers in making good decisions about product manufacturability have a significant role to play. However, the nature of the rules, methods, and tools should change to assist designers in understanding the design freedom allowed by AM and, potentially, aiding the designer in exploring the resulting open design spaces, while ensuring that manufacturing constraints (yes, AM technologies do have constraints) are not violated.

To illustrate the differences between DFM and DFAM, this section will conclude with two examples. The first involves typical injection molding considerations, that of undercuts and feature detail. Consider the camera spool part shown in Fig. 17.1 [5]. The various ribs and pockets are features that contribute to the time and cost of machining the mold in which the spools will be molded. Such feature detail is not relevant to AM processes since ribs can be added easily during processing in an AM machine. A similar result relates to undercuts. This spool design has at least one undercut, since it cannot be oriented in a mold consisting of only two mold pieces (core and cavity), while enabling the mold halves to be separated and the part removed. Most probably, the spool will be oriented so that

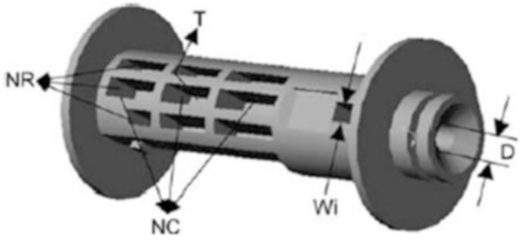

Fig. 17.1 Camera spool example

the mold closure direction is parallel to the walls of the ribs. In this manner, the core and cavity mold halves form most of the spool features, including the ribs (or pockets), the flanges near the ends, and the groove seen at the right end. In this orientation, the hole in the right end cannot be formed using the core and/or cavity. A third moving mold section, called a side action, is needed to form the hole. In AM processes, it is not necessary to be so concerned about the relative position and orientation of features, since, again, AM machines can fabricate features regardless of their position in the part.

In design for assembly, two main considerations are often offered to reduce assembly time, cost, and difficulties: minimize the number of parts and eliminate fasteners. Both considerations translate directly to fewer assembly operations, the primary driver for assembly costs [3]. To minimize parts and fasteners, integrated part designs typically become much more complex and costly to manufacture. Design for manufacture and design for assembly will often be repeated, iteratively, until an optimal solution is found; one where the increasing manufacturing costs for more complex components are no longer compensated by the assembly cost savings.

The designs in Fig. 17.2 show two very different approaches to designing ducts for aircraft [6, 7]. This example represents a design concept for conveying cooling air to electronic units in military aircraft, but could apply to many different applications. The first design is a typical approach using parts fabricated by conventional manufacturing processes (stamping, sheet metal forming, assembly using screws, etc.). In contrast, the approach on the right illustrates the benefits of taking design for assembly guidelines to their extreme: the best way to reduce assembly difficulties and costs is to eliminate assembly operations altogether! The resulting design replaces 16 parts and fasteners with 1 part that exhibits integrated flow vanes and other performance enhancing features. However, this integrated design cannot be fabricated using conventional manufacturing techniques and is only manufacturable using AM.

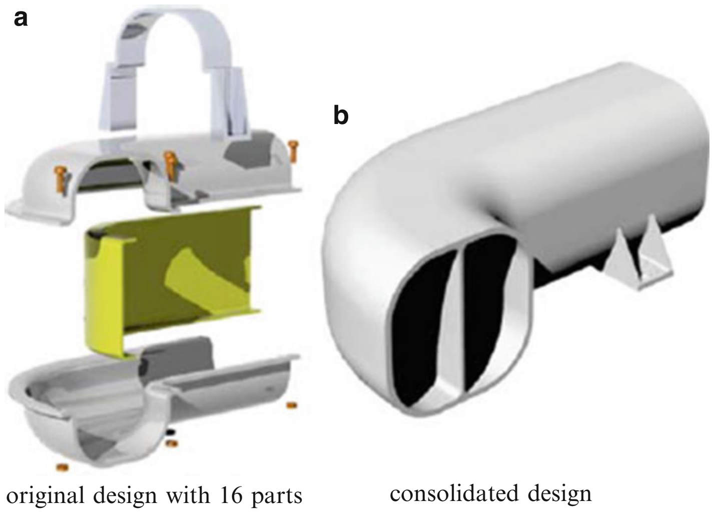

Fig. 17.2 Aircraft duct example

17.3 AM Unique Capabilities

The layer-based additive nature of AM leads to unique capabilities in comparison with most other manufacturing processes. After explaining these uniquenesses, several examples and classes of applications will be presented in the next section. The unique capabilities mentioned at the beginning of the chapter were:

- Shape complexity: it is possible to build virtually any shape
- Hierarchical complexity: features can be designed with shape complexity across multiple size scales
- Functional complexity: functional devices (not just individual piece-parts) can be produced in one build
- Material complexity: material can be processed one point, or one layer, at a time as a single material or as a combination of materials

To date, primarily shape complexity has been used to enable production of end-use parts, but applications taking advantage of the other capabilities, particularly material complexity, are being developed.

17.3.1 Shape Complexity

In AM, the capability to fabricate a layer is unrelated to the layer's shape. For example, the lasers in vat photopolymerization (VP) and powder bed fusion (PBF)

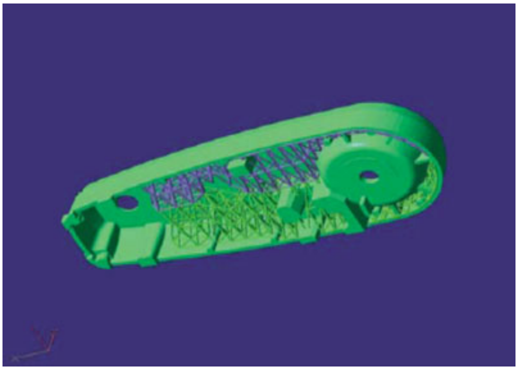

Fig. 17.3 Robot link stiffened with lattice structure

processes can reach any point in a part's cross section and process material there. As such, part complexity is virtually unlimited. This is in stark contrast to the limitations imposed by machining or injection molding, two common processes. In machining, tool accessibility is a key limitation that governs part complexity. In injection molding, the need to separate mold pieces and eject parts greatly limits part complexity.

A related capability is to enable custom-designed geometries. In production using AM, it does not matter if one part has a different shape than the previously produced part. Furthermore, no hard tooling or fixtures are necessary, which implies that lot sizes of one can be economically feasible. This is tremendously powerful for medical applications, for example, since everyone's body shape is different. Also, consider the design of a high-speed robot arm. High stiffness and low weight are desired typically. With AM, the capability is enabled to put material where it can be utilized best. The link from a commercial Adept robot (Cobra 600) shown in Fig. 17.3 has been stiffened with a custom-designed lattice structure that conforms to the link's shape. Preliminary calculations show that weight reductions of 25 % are achieved readily with this lattice structure and that much greater improvements are possible. More generally, AM processes free designers from being limited to shapes that can be fabricated using conventional manufacturing processes.

Another factor enabling lot sizes of one, and shape complexity, is the capability for automated process planning. Straightforward geometric operations can be performed on AMF or STL files (or CAD models) to decompose the part model into operations that an AM machine can perform. Although CNC has improved greatly, many more manual steps are typically utilized in process planning and generating machine code for CNC than for AM.

17.3.2 Hierarchical Complexity

Similar to shape complexity, AM enables the design of hierarchical complexity across several orders of magnitude in length scale. This includes nano/

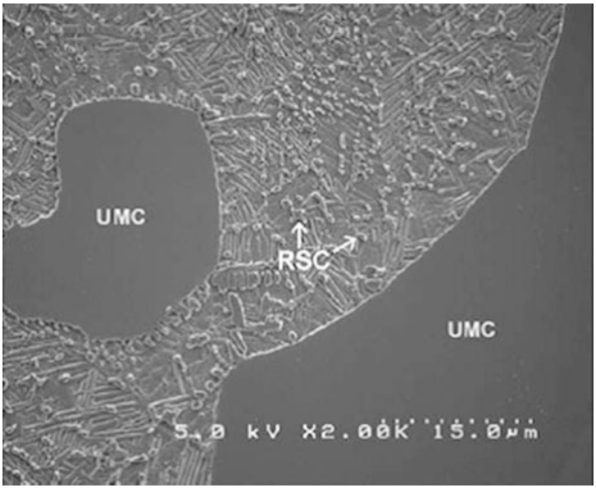

Fig. 17.4 Sixty percent CP-Ti, 40 % TiC composite made using LENS. The ratio of un-melted carbides (UMCs) to resolidified carbides (RSCs) within the Ti matrix is controlled by varying LENS process parameters

microstructures, mesostructures, and part-scale macrostructures. We will start with material microstructures.

One set of processes, which has been studied extensively with respect to hierarchical complexity, are the directed energy deposition (DED) processes. In LENS, for instance, the nano/microstructure can be tailored in a particular location by controlling the size and cooling rate of the melt pool. As a result, the size and distribution of precipitates (nanoscale) and secondary particles (microscale), for example, can be changed by locally modifying the laser power and scan rate. Figure 17.4 illustrates the types of microstructural features which can be formed when using LENS to process mixtures of TiC in Ti to form a composite structure. There are several features of the microstructure which can be controlled. In cases of lower laser energy densities, there is a greater proportion of unmelted carbide (UMC) particles within the microstructure. At higher energy densities more of the TiC particles melt and precipitate as resolidified carbides (RSC). In addition, as the RSC have a different stoichiometry (TiC transforms to $TiC_{0.65}$); for a given initial mixture of TiC and Ti, the more RSC that is present in the final microstructure, the less Ti matrix material is present. The resulting microstructures can thus have very different material and mechanical properties. If sufficient RSCs are precipitated to consume the Ti matrix material, then the structure becomes very brittle. In contrast, when most of the TiC is present as UMCs, the structure is more ductile but is less resistant to abrasive wear.

In addition to the nano/microstructure illustration above, DED technologies have been shown to be capable of producing equiaxed, columnar, directionally solidified, and single-crystal grain structures. These various types of nano/microstructures can be achieved by careful control of the process parameters for a particular material, and can vary from point to point within a structure. In many cases, for laser or electron beam PBF processes for metals, these variations are also

Fig. 17.5 Pulley-driven snake-like robot

achievable. Similarly, by varying either the materials present (when using a multimaterial AM system) or the processing of the materials, this type of nano/microstructure control is also possible in ME, material jetting, VP, and sheet lamination AM technologies as well. These related possibilities are further explored below with respect to material complexity.

The ability to change the mesostructure of a part is typically associated with the application of cellular structures, such as honeycombs, foams, or lattices, to fill certain regions of a geometry. This is often done to increase a part's strength to weight or stiffness to weight ratio. These structures are discussed in more detail in Sect. 17.5.2.

When considered together, the ability to simultaneously control a part's nano/microstructure, mesostructure, and macrostructure simply by changing process parameters and CAD data is a capability of AM which is unparalleled using conventional manufacturing.

17.3.3 Functional Complexity

When building parts in an additive manner, one always has access to the inside of the part. Two capabilities are enabled by this. First, by carefully controlling the fabrication of each layer, it is possible to fabricate operational mechanisms in some AM processes. By ensuring that clearances between links are adequate, revolute or translational joints can be created. Second, components have been inserted into parts being built in VP, ME, PBF, sheet lamination, and other AM machines, enabling in situ assembly.

A wide variety of kinematic joints has been fabricated directly in VP, ME, and PBF technologies, including vertical and horizontal prismatic, revolute, cylindrical, spherical, and Hooke joints. Figure 17.5 shows one example of a pulley-driven, snake-like robot with many revolute joints that was built as assembled in the SLA-3500 machine at Georgia Tech.

Similar studies have been performed using material extrusion (ME) and PBF processes. The research group at Rutgers University led by Dr. Mavroidis [8] demonstrated that the same joint geometries could be fabricated by both ME and PBF machines and similar clearances were needed in both machine types. In PBF,

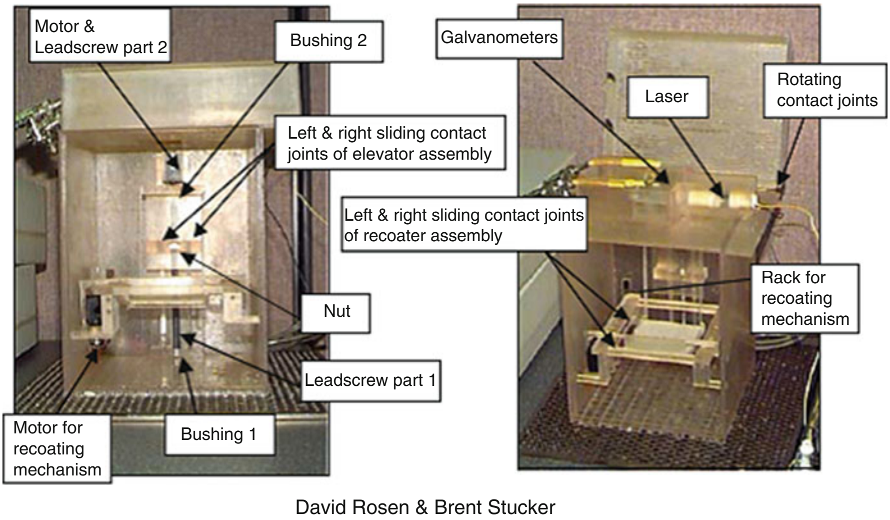

Fig. 17.6 SLA-250 model built in an SLA-250 machine with 11 embedded components

loose powder must be removed from the joint locations to enable relative joint motion. In ME, the usage of soluble support material ensures that joints can be movable after post-processing in a suitable solvent.

In the construction of functional prototypes, it is often advantageous to embed components into parts while building them in AM machines. This avoids post-fabrication assembly and can greatly reduce the number of separate parts that have to be fabricated and assembled.

For example, it is possible to fabricate VP devices with a wide range of embedded components, including small metal parts (bolts, nuts, bushing), electric motors, gears, silicon wafers, printed circuit boards, and strip sensors. Furthermore, VP resins tend to adhere well to embedded components, reducing the need for fasteners. Shown in Fig. 17.6 is a model of an SLA-250 machine that was built in the SLA-250 at Georgia Tech [9]. This 150 × 150 × 260 mm model was built at 1:¼ scale, with seven inserted components, four sliding contact joints, and one rotating contact joint. The recoating blade slides back-and-forth across the vat region, driven by an electric motor and gear train. Similarly, the elevator and platform translate vertically, driven by a second electric motor and leadscrew. The laser pointer and galvanometers worked to draw patterns on the platform, but these three components were assembled after the build, rather than subjecting them to being dipped into the resin vat. Build time was approximately 75 h, including time to pause the build and insert components.

Other researchers have also demonstrated the capability of building functional devices, including the Mavroidis group and Dr. Cutkosky’s group at Stanford University [10]. Device complexity is greatly facilitated when the capability to

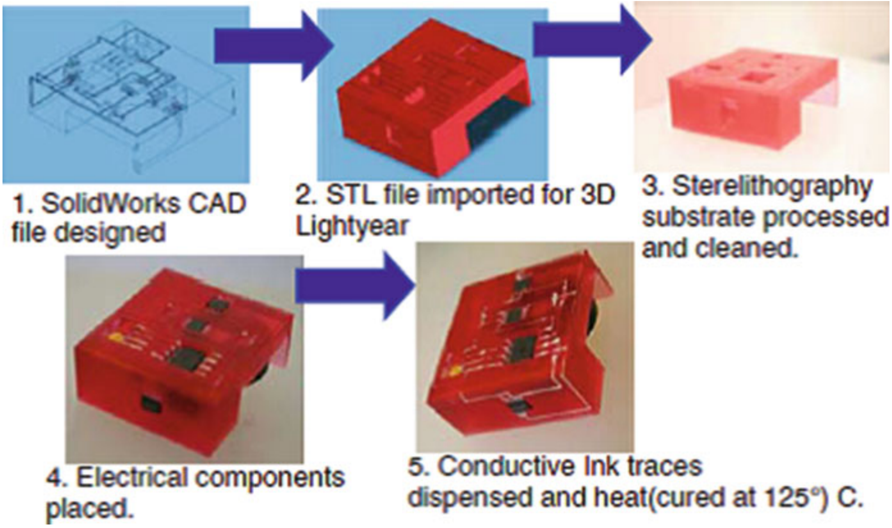

Fig. 17.7 Fabrication of a magnetic flux sensor using VP and DW (courtesy of W.M. Keck Center for 3D Innovation at The University of Texas at El Paso)

fabricate kinematic joints is coupled with embedded inserts since functional mechanisms can be fabricated entirely within the VP vat, greatly simplifying the prototyping process.

Functional complexity can also 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 VP or ME and DW. Figure 17.7 illustrates the process plan for fabrication of a magnetic flux sensor using VP and a nozzle-based DW process. Researchers have demonstrated similar capabilities with ME, sheet lamination, PBF, and other technologies as well.

17.3.4 Material Complexity

Since material is processed point to point in many of the AM technologies, the opportunity is available to process the material differently at different points, as illustrated above, causing different material properties in different regions of the part. In addition, many AM technologies enable changing material composition gradually or abruptly during the build process. New applications will emerge to take advantage of these characteristics.

The concept of functionally graded materials, or heterogeneous materials, has received considerable attention [11], but manufacturing useful parts from these materials often has been problematic. Consider a turbine blade for a jet engine. The outside of the blade must be resistant to high temperatures and be very stiff to prevent the blade from elongating significantly during operation. The blade root must be ductile and have high fatigue life. Blade interiors must have high heat conductivity so that blades can be cooled. This is an example of a part with complex shape that requires different material properties in different regions. No single material is ideal for this range of properties. Hence, if it was possible to fabricate complex parts with varying material composition and properties, turbine blades and similar parts could benefit tremendously.

DED processes, such as LENS and DMD machines, have demonstrated capability for fabricating graded material compositions. Ongoing work in this direction is promising. Graded and multimaterial compositions are used in the repair of damaged or worn components using DED machines, and the design and fabrication of new components is being explored around the world. One such application for improved components that is receiving considerable attention is the fabrication of higher-performance orthopedic implants. In this case, certain regions of the implant require excellent bone adhesion, whereas in other regions the bearing surfaces must be optimized to minimize the implant's wear properties. Thus, by changing the composition of the material from the bone in-growth region to the bearing surface, the overall performance of the implant can be improved.

As described in Chap. 7, Objet Geometries Ltd. (now Stratasys) introduced in 2007 the first commercial AM machine, their Connex500™ system, capable of ink-jet deposition of several polymer materials in one build. Their technology, called PolyJet Matrix™, is an evolution of their printing technology. Recall that Objet uses large arrays of printing nozzles (up to 3,000) to quickly print parts using photopolymer materials. More recently, both Stratasys and 3D Systems have introduced full color printing technology using ink-jet printing of photopolymers that exhibit a much wider range of mechanical properties than Objet's original materials.

For many years, ME machines have been shipped with multiple nozzles for multimaterial deposition. Although one or more nozzles is typically utilized for support materials and the other for build materials, many researchers and industrial practitioners have utilized different feedstock materials in two banks of nozzles to create multimaterial constructs. As can easily be imagined, it would be quite easy, conceptually, to add more nozzles, and thus easily increase the number of materials which can be deposited in a single build. In fact, this concept has been utilized by a number of researchers in their own custom-built extrusion-based machines, primarily by those investigating extrusion-based processes for biomedical materials research.

A significant issue hindering the adoption of AM's material complexity is the lack of design and CAD tools that enable representation and reasoning with multiple materials. This will be explored more completely in Sect. 17.6.

17.4 Core DFAM Concepts and Objectives

Given these unique capabilities of AM, we can articulate some core DFAM concepts and objectives. In contrast to DFM, we believe the objective of DFAM should be to:

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

To realize this objective, designers should keep in mind several guidelines when designing products:

- AM enables the usage of complex geometry in achieving design goals without incurring time or cost penalties compared with simple geometry.
- As a corollary to the first guideline, it is often possible to consolidate parts, integrating features into more complex parts and avoiding assembly issues.
- AM enables the usage of customized geometry and parts by direct production from 3D data.
- With the emergence of commercial multimaterial AM machines, designers should explore multifunctional part designs that combine geometric and material complexity capabilities.
- AM allows designers to ignore all of the constraints imposed by conventional manufacturing processes (although AM-specific constraints might be imposed).

17.4.1 Complex Geometry

As was discussed earlier, AM processes are capable of fabricating parts with complex geometry. The layer-by-layer fabrication approach means that the shapes of part cross sections can be arbitrarily complex, up to the resolution of the process. For example, VP and PBF processes can fabricate features almost as thin as their laser spot sizes. In material jetting processes, features in the layer can be the size of several printed droplets. In the Z direction (build direction), the discussion of feature complexity becomes more complicated. In principle, features can be as thin as a layer thickness; however, in practice, features typically are several layers thick. Stresses during the build, such as produced by recoating in VP, can limit Z resolution. Also, overcure or “bonus Z” effects occur in laser-based processes and tend to create regions that are thicker than a single layer. The need to remove the support structures necessary for some AM processes may also limit geometric complexity and/or feature size. Each AM process has its individual characteristics and will take some time to learn. But in general the geometric complexity of AM processes far exceeds that of conventional manufacturing processes.

17.4.2 Integrated Assemblies

The capability for complex geometry enables other practices. As was demonstrated at the end of Sect. 17.2, several parts can be replaced with a single, more complex part in many cases. Even when two or more components must be able to move with respect to one another, such as in a ball-and-socket joint, AM can build these components fully assembled. These capabilities enable the integration of features from multiple parts, possibly yielding better performance. Additionally, a reduction in the number of assembly operations can have a tremendous impact on production costs and difficulties for products.

As is evident from conventional DFM practices, design changes to facilitate or eliminate assembly operations can lead to much larger reductions in production costs than changes to facilitate part manufacture [3]. This is true, at least in part, due to the elimination of any assembly tooling that may have been required. Although conventional DFM guidelines for part manufacturing are not relevant to AM, the design-for-assembly guidelines remain relevant and perhaps even more important. Other advantages exist for the consolidation of parts. For example, a reduction in part count reduces product complexity from management and production perspectives. Fewer parts need to be tracked, sourced, inspected, etc. The need for spare or replacement parts decreases. Furthermore, the need to warehouse tooling to fabricate the parts can be eliminated. In summary, part consolidation can lead to significant savings across the entire enterprise.

17.4.3 Customized Geometry

Consistent with the capability of complex geometry, AM processes can fabricate custom geometries. This has been demonstrated by a series of examples throughout this book related to direct digital manufacturing and biomedical applications. A good example is that of hearing aid shells (Sect. 16.2). Each shell must be customized for an individual's particular ear canal geometry. In VP or PBF machines, hundreds or thousands of shells, each of a different geometry, can be built at the same time in a single machine. Mass customization, instead of mass production, can be realized quite readily. The lack of generic software tools for mass customization, rather than limitations of the hardware, is the key limitation when considering AM for mass customization.

17.4.4 Multifunctional Designs

Multifunctionality is simply the achievement of multiple functions, or purposes, with a single part. This is commonly achieved when performing part consolidation, but the capability of material complexity enables much more ambitious explorations of design possibilities. For example, if a part needs to be stiff in one location, but flexible in another, several AM processes could be used to fabricate such a design simply by varying material composition. Another example is a heat exchanger, that also serves a structural purpose, which could be fabricated by grading steel and copper alloys. By combining geometric and material complexity, very high performance devices can be fabricated. In many cases, designers will need to develop new design concepts and then explore them, since many domains will lack examples of previously successful designs.

17.4.5 Elimination of Conventional DFM Constraints

Since the 1980s, engineering design has changed considerably due to the impact of DFM, concurrent engineering, and integrated product-process teaming practices. A significant amount of time and funds were dedicated to learning about the capabilities and constraints imposed by other parts of the organization. As should be clear from this chapter, AM processes have the potential to reduce the burden on organizations to have integrated product development teams that spend large amounts of time resolving constraints and conflicts. With AM, designers have to learn far fewer manufacturing constraints. The embrace of DFM has resulted in a design culture where the design space is limited from the earliest conceptual design stage to those designs that are manufacturable using conventional techniques. With AM, these design constraints are no longer valid, and the designer can have much greater design freedom.

As such, the challenge in DFAM is not so much the understanding of the effects of manufacturing constraints. Rather it is the difficulty in exploring new design spaces, in innovating new product structures, and in thinking about products in unconventional ways. These do not have to be difficulties, since they are really opportunities. However, the engineering community must be open to the possibilities and learn to exercise their collective creativity.

17.5 Exploring Design Freedoms

With the unique capabilities of AM identified, we can illustrate how to utilize those capabilities through a set of examples. In one approach, companies have achieved significant part consolidation, combining several parts into a single part. In a second approach, researchers have demonstrated how hierarchical structures can result from structuring the material in parts using mesoscale or microscale features to produce the so-called cellular materials. In the third approach, industrial designers have explored new design concepts for some everyday products, such as plates, chairs, and clothing.

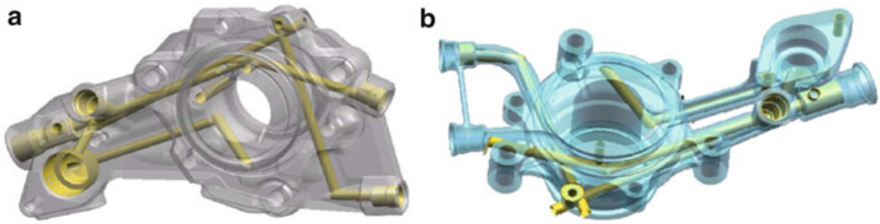

Fig. 17.8 Diesel front plate example. (**a**) Original design. (**b**) Redesigned for additive manufacturing

17.5.1 Part Consolidation and Redesign

The characteristics of geometric complexity and suitability for low-volume production combine to yield substantial benefits in many cases for consolidating parts into a smaller number of more complex parts that are then fabricated using an AM process. This has several significant advantages over designs with multiple parts. First, dedicated tooling for multiple parts is not required. Potential assembly difficulties are avoided. Assembly tooling, such as fixtures, is not needed. Fasteners can often be eliminated. Finally, it is often possible to design the consolidated parts to perform better than the assemblies.

A well-known example that illustrates these advantages was shown in Fig. 17.2, that of a prototypical duct for military aircraft [6, 7]. The design shows a typical traditional design with many formed and rotomolded plastic parts, some formed sheet-metal parts, and fasteners [12]. The example was from the pioneering work of the Boeing Phantom Works Advanced Direct Digital Manufacturing group in retrofitting F-18 fighter jets with dozens of parts produced using PBF. Many of these parts replaced standard ducting components to deliver cooling air to electronics modules. Significant part reductions, elimination of fasteners, and optimization of shapes are illustrative of the advances made by Boeing. Through these methods, many part manufacturing tools and assembly operations were eliminated.

A second example, from Loughborough University, illustrates the advantages of reconceptualizing the design of a component based on the ability to avoid limitations of conventional manufacturing processes. Figure 17.8 shows a front plate design for a diesel engine [7]. The channels through which fuel or oil flow are gun drilled. As a result, they are straight; furthermore, plugs need to be added to plug up the holes through the housing that enabled the channels to be drilled. The redesign shown in Fig. 17.8b was developed by designing the flow channels to ensure efficient flows, then adding a minimal amount of additional material to provide structural integrity. As a result, the part is smaller, lighter, and has better performance than the original design.

17.5.2 Hierarchical Structures

The basic idea of hierarchical structures is that features at one size scale can have smaller features added to them, and each of those smaller features can have smaller features added, etc. Tailored nano/microstructures are one example. Textures added to surfaces of parts are another example. In addition, cellular materials (materials with voids), including foams, honeycombs, and lattice structures, are a third example of hierarchical feature. To illustrate the benefits of designing with hierarchical flexibility, we will focus on cellular materials in this section.

The concept of designed cellular materials is motivated by the desire to put material only where it is needed for a specific application. 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 [13]. When the characteristic lengths of the cells are in the range of 0.1–10 mm, we refer to these materials as mesostructured materials. Mesostructured materials that are not produced using stochastic processes (e.g., foaming) are called designed cellular materials.

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 [14]. Lattice structures tend to have geometry variations in three dimensions; as is illustrated in Fig. 17.9. As pointed out in [15], the strength of foams scales as $\rho^{1.5}$, whereas lattice structure strength scales as ρ, where ρ is the volumetric density of the material. As a result, lattices with a $\rho = 0.1$ are about three times stronger per unit weight than a typical foam. The strength differences lie in the nature of material deformation: the foam is governed by cell wall bending, while lattice elements stretch and compress. The examples shown in Fig. 17.9 utilize the octet-truss (shown on the *left*), but many other lattice structures have been developed and studied (e.g., kagome, Kelvin foam) [16, 17].

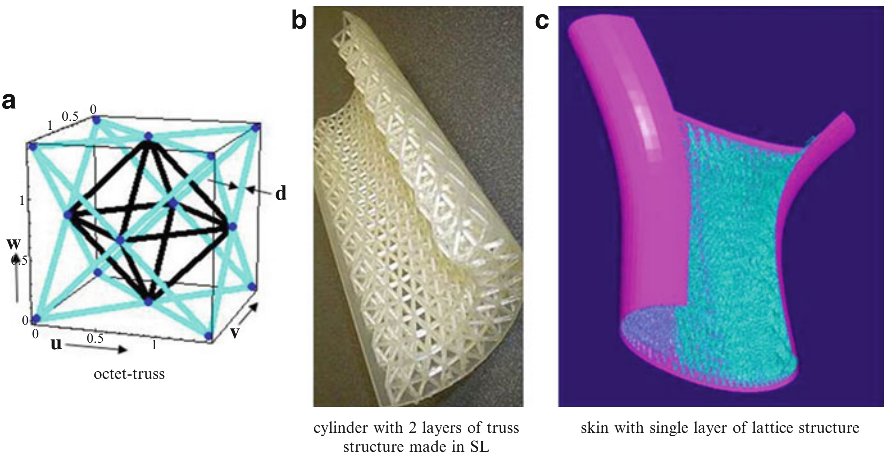

Fig. 17.9 Octet-truss unit cell and example parts with octet-truss mesostructures

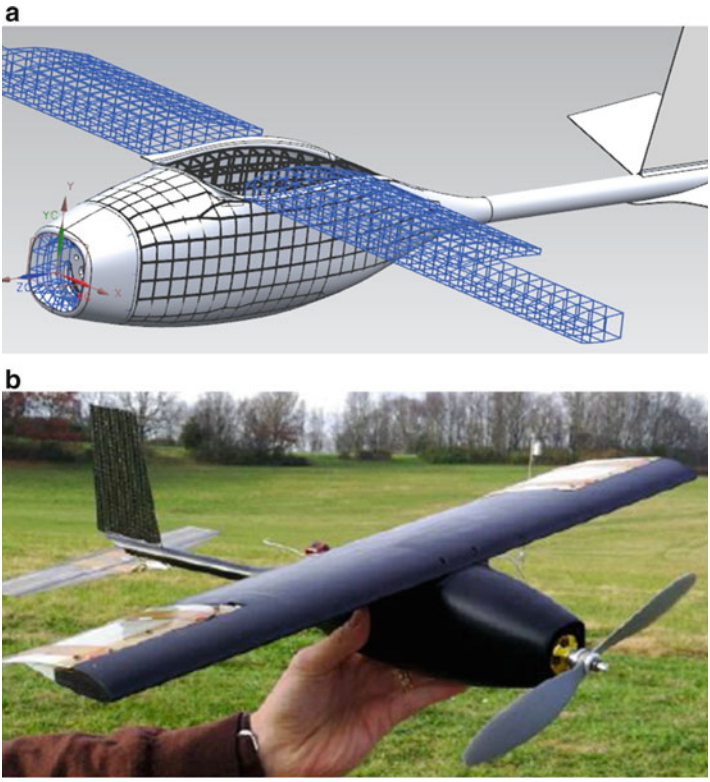

Fig. 17.10 Lattice structure-based UAV design. (**a**) lattice structure designs for fuselage and wings. (**b**) assembled UAV ready for test flight

The parts shown in Fig. 17.9b, c illustrate one method of developing stiff, lightweight structures, that of using a thin part wall, or skin, and stiffening it with cellular structure. Another method could involve filling a volume with the cellular structures. Using either approach often results in part designs with thousands of shape elements (beams, struts, walls, etc.). Most commercial CAD systems cannot perform geometric modeling operations on designs with more than 1,000–2,000 elements. As a result, the design in Fig. 17.9c, which has almost 18,000 shape elements, cannot be modeled using conventional CAD software. Instead, new CAD technologies must be developed that are capable of modeling such complex geometries [18]; this is the subject of Sect. 17.6.

Several groups designed unmanned aerial vehicles (UAV) components by applying various cellular structure design approaches. Figure 17.10 shows a hand-held UAV, the Streetflyer from AVID LLC, that was redesigned to utilize lattice structure reinforcement. The original design of the UAV utilized carbon fiber skins for the fuselage and wings, but required many assembly operations to add stiffeners, fastening features, and mounting features to the components. In contrast, by designing for AM, the lattice structure-based design had such features and stiffeners designed in. Experts at Paramount Industries, a 3D Systems company, fabricated the fuselage and wings in Duraform using PBF. Test flights demonstrated that the PBF-fabricated UAV performed well and, even though the UAV was not optimized, its performance approached that of the carbon fiber production version.

17.5.3 Industrial Design Applications

Some very intriguing approaches to product design have been demonstrated that take advantage of the shape complexity capabilities of AM, as well as some material characteristics. A leader in this field was a small company in The Netherlands called Freedom of Creation (FOC), founded by Janne Kytannen, which was purchased by 3D Systems in the early 2010s. See: http://www.freedomofcreation.com.

FOC began operations in the late 1990s. Their first commercial products were lamp shades fabricated in VP and PBF [20], an example of which is shown in Fig. 17.11a. They have since developed many families of lampshade designs. In 2003, they partnered with Materialise to market lampshades, which retail for 300 to 6,000 euros (as of 2009).

Many other classes of products have been developed, including chairs and stools, handbags, bowls, trays, and other specialty items. See Fig. 17.11b, c for examples of other products. Also, they have partnered with large and small organizations to develop special “give-aways” for major occasions, many of which were designed to be manufactured via AM.

In the early 2000s, they developed the concept of manufacturing textiles. Their early designs were of chain-mail construction, manufactured in PBF. Since then, they have developed several lines of products using similar concepts, including handbags, other types of bags, and even shower scrubs.

More recently, quite a few other companies have demonstrated very innovative designs of housewares, clothing, fashion accessories, and even shoes. Fashion shows have focused on AM-fabricated clothes, parts of clothing, and accessories. Some examples from 2014 include Anouk Wipprecht’s electrified 3D printed dresses, hats/headpieces by Gabriela Ligenza, Ray Civello, and Stephen Ma, and dresses and accessories from Iris Van Herpen.

Another source of inspiration comes from browsing the virtual storefronts on shapeways.com and ponoko.com, where individual entrepreneurs and small companies can offer custom designs. Everything from jewelry to candle holders to bird houses can be found on these sites. Methods of manufacturing the designs offered on each storefront need to be provided and many times the only methods are through AM. Some sites provide design guidelines, suggestions, or even specially developed CAD tools.

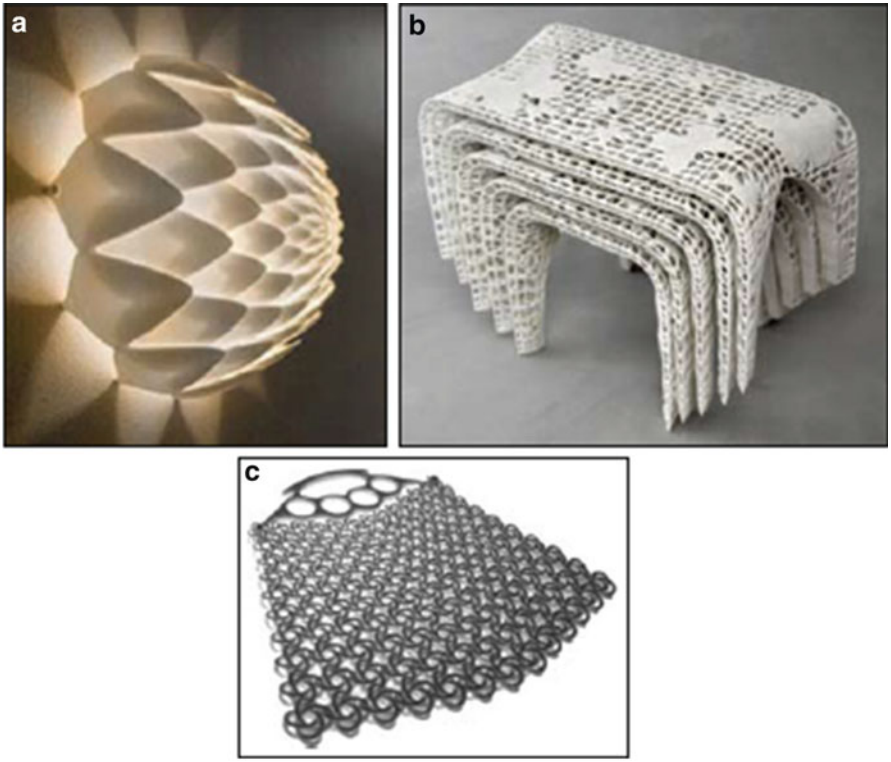

Fig. 17.11 Example products from Freedom of Creation: (**a**) a wall-mounted lampshade, Dahlia light, designed by Janne Kyttanen for Freedom Of Creation, (**b**) stacking footstools, Monarch Stools, designed by Janne Kyttanen for Freedom Of Creation, and (**c**) a handbag, Punch Bag, designed by Jiri Evenhuis and Janne Kyttanen for Freedom Of Creation

17.6 CAD Tools for AM

With tremendous design potential waiting for designers to explore, they need good tools to support their exploration. In this section, we present challenges and technologies associated with mechanical CAD systems.

17.6.1 Challenges for CAD

Current solid-modeling-based CAD systems have several limitations that make them less than ideal for taking advantage of the unique capabilities of AM machines. For some applications, CAD is a bottleneck in creating novel shapes and structures, in describing desired part properties, and in specifying material compositions. These representational problems imply difficulties in driving process

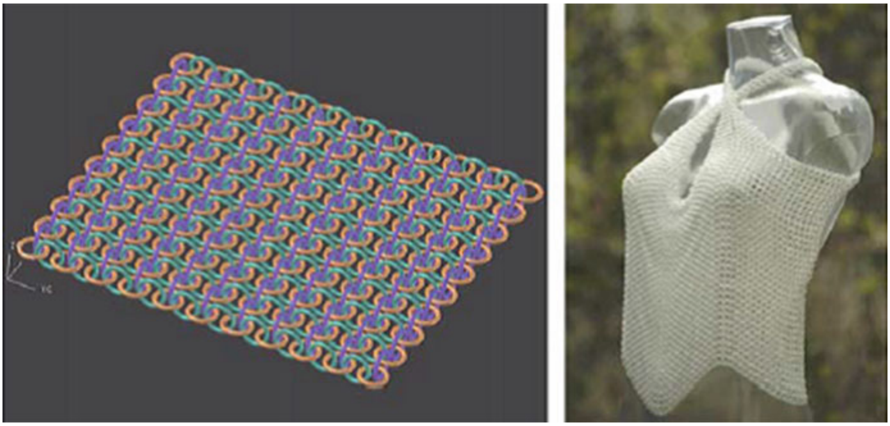

Fig. 17.12 Example of textiles produced using PBF

planning and other analysis activities. Potentially, this issue will slow the adoption of AM technologies for use in production manufacture. More specifically, the challenges for CAD can be stated as:

- Geometric complexity—need to support models with tens and hundreds of thousands of features.
- Physically based material representations—material compositions and distributions must be represented and must be physically meaningful.
- Physically based property representations—desired distributions of physical and mechanical properties must be represented and tested for their physical basis.

One example of the geometric complexity issue is illustrated by the prototype textile application, from Loughborough University and Freedom of Creation, shown in Fig. 17.12 [21]. On the left is a "chain mail"-like configuration of many small rings. On the right is an example garment fabricated on a PBF machine in a Duraform material. The researchers desired to fold up the CAD model of the garment so that it occupied a very small region in the machine's build platform, which would maximize the throughput of the PBF machine for production purposes. The Loughborough researchers had great difficulty modeling the collection of thousands of rings that comprise the garment in a commercial solid-modeling CAD system. Instead they developed their own CAD system for textile and similar structured surface applications over several years. However, having to develop custom CAD systems for specific applications will be a significant barrier to widespread adoption of AM.

Two CAD challenges can be illustrated by some simple examples. The Stratasys Connex 500 material jetting machine can deposit several different materials while building one part. To drive the machine, Stratasys needed to develop a new software tool that allows users to specify materials in different regions of STL files. It would be far better to be able to specify material composition in the original CAD system, so that vendor or machine-specific tools are not needed. The second example was a research project from the Fraunhofer Institute for Manufacturing and Advanced Materials (IFAM) in Bremen, Germany [22]. They developed a two-binder system for 3D Printing technology, where one binder is traditional and one is carbon laden. Their goal was to produce gradient strength steel parts by depositing the carbon according to a desired distribution of hardness. The model of hardness will be converted into a representation of carbon distribution, which will be converted into carbon-laden binder deposition commands for the 3DP system. After building, the part will be heat treated to diffuse the carbon into the steel. As a result, this application illustrates the need to represent distributions of mechanical properties (hardness) and material composition (carbon, steel), and relate these to processing conditions. The IFAM researchers developed a software system for this application.

17.6.2 Solid-Modeling CAD Systems

Parametric, solid-modeling CAD systems are used throughout much of the world for mechanical product development and are used in university education and research. Such systems, such as ProEngineer, Unigraphics, SolidEdge, CATIA, and SolidWorks, are very good for representing shapes of most engineered parts. Their feature-based modeling approaches enable fast design of parts with many types of typical shape elements. Assembly modeling capabilities provide means for automatically positioning parts within assemblies and for enforcing assembly relationships when part sizes are changed.

Commercial CAD systems typically have a hybrid CSG-BRep (constructive solid geometry—boundary representation) internal representation of part geometry and topology. With the CSG part of the representation, part construction history is maintained as a sequence of feature creation, operation, and modification processes. With the BRep part of the representation, part surfaces are represented directly and exactly. Adjacencies among all points, curves, surfaces, and solids are maintained. A tremendous amount of information is represented, all of which has its purposes for providing design interactions, fast graphics, mass properties, and interfaces to other CAD/CAM/CAE tools.

For parts with dozens or hundreds of surfaces, commercial CAD systems run with interactive speeds, for most types of design operations, on typical personal computers. When more than 1,000 surfaces or parts are modeled, the CAD systems tend to run very slowly and use hundreds of MB or several GB of memory. For the textile part, Fig. 17.12, thousands of rings comprise the garment. However, they have the same simple shape, that of a torus. A different type of application is that of hierarchical structures, where feature sizes span several orders of magnitude. An example is that of a multimaterial mold with conformal cooling channels, where the cooling channels have small fins or other protrusions to enhance heat transfer. The fins or protrusions may have sizes of 0.01 mm, while the channels may be 10 mm in diameter, and the mold may be 400 mm long. The central region of the mold may use a high conductivity, high toughness material composition, whereas the surface of the mold may have a high hardness material composition, where a conformal, gradient transition occurs within a region near the surface of the mold. As a result, the mold model may have many thousands of small features and must also represent a gradient material composition that is derived from knowledge of the geometric features. In addition, the range of size scales may cause problems in managing internal tolerances in the CAD system. Current CAD systems are incapable of representing the thousands of features or the graded material composition o f this mold example.

In summary, two main geometry-related capabilities are needed to support many emerging design applications, particularly when AM manufacturing processes will be utilized:

- Representation of tens or hundreds of thousands of features, surfaces, and parts.
- Managing features, materials, surfaces, and parts across size ranges of 4–6 orders of magnitude.

The ISO STEP standard provides a data exchange representation for solid geometry, material composition, and some other properties. However, it is intended for exchanging product information among CAD, CAM, and CAE systems, not for product development and manufacturing purposes. That is, the STEP representation was not developed for use within modeling and processing applications. A good assessment of its usefulness in representing parts with heterogeneous materials for AM manufacturing is given in reference [11], although at present the standards community is revisiting the potential usage of STEP for AM.

As mentioned above, the first challenge for CAD systems is geometric complexity. The second challenge for CAD systems is to directly represent materials, to specify a part's material composition. As a result, CAD models cannot be used to represent parts with multiple materials or composite materials. Material composition representations are needed for parts with graded interfaces, functionally graded materials, and even simpler cases of particle or fiber filler materials. Furthermore, CAD models can only provide geometric information for other applications, such as manufacturing or analysis, not complex multiple material information, which limits their usefulness. This type of limitation is clear when one considers the ink-jet printing examples mentioned so far (e.g., Stratasys multimaterial printer, IFAM carbon-laden inks). In the IFAM case, the addition of carbon to steel deals with the relatively well understood area of carbon steels. In other applications, novel material combinations that are less understood may be of interest. Two main issues arise, including the need to:

- Represent desired material compositions at appropriate size scales.
- Determine the extent to which desired material compositions are achievable.

Without a high fidelity representation of materials, it will not be possible to directly fabricate parts using emerging AM processes. Furthermore, DFM practices will be difficult to support. Together, these limitations may prevent the adoption of AM processes for applications where fast response to orders is needed.

The third challenge, that of representing physically based property distributions, is perhaps the most challenging. The IFAM example of relating desired hardness to carbon content is a relatively simple case. More generally, the geometry, materials, processing, and property information for a design must be represented and integrated. Without such integrated CAD models, it will be very difficult to design parts with desired properties. Analysis and manufacturing applications will not be enabled. The capability of utilizing AM processes to their fullest extent will not be realized. In summary, two main issues are evident:

- Process–structure–property relationships for materials must be integrated into geometric representations of CAD models.
- CAD system capabilities must be developed that enable designers to synthesize a part, its material composition, and its manufacturing methods to meet specifications.

17.6.3 Promising CAD Technologies

The challenges raised in the previous subsection are difficult and go against the directions of decades of CAD research and development. Some CAD technologies on the horizon, however, have promise in meeting these challenges. Two broad categories of technologies will be presented here, implicit modeling and multiscale modeling. Additional technologies can be combined to yield a CAD system that can be used to design components for a wide variety of purposes and with a wide variety of material compositions and geometric complexities.

17.6.3.1 Proposed DFAM System

Figure 17.13 shows one proposed DFAM system [19]. To the right in the figure, the designer can construct a DFAM synthesis problem, using an existing problem template if desired. For different problem types, different solution methods and algorithms will be available. Analysis codes, including FEA, boundary element, and specialty codes, will be integrated to determine design behavior. In the middle, the heterogeneous solid modeler (HSM) is illustrated that consists of implicit and multiscale modeling technologies. Heterogeneous solid modeling denotes that material and other property information will be modeled along with geometry. Libraries of materials and mesostructures enable rapid construction of design models. To the left, the manufacturing modules are shown. Both process planning and simulation modules are important in this system. After planning a manufacturing process, the idea is that the process will be simulated on the current design to determine the as-manufactured shapes, sizes, mesostructures, and

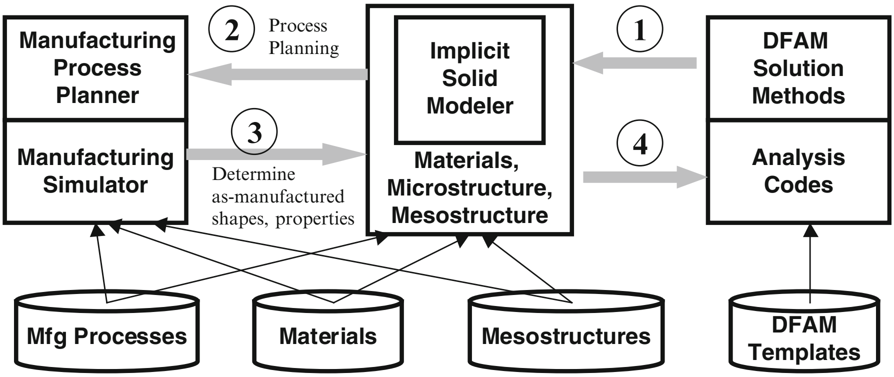

Fig. 17.13 DFAM system and overall structure

microstructures. The as-manufactured model will then be analyzed to determine whether or not it actually meets design objectives.

The proposed geometric representation is a combination of implicit, nonmanifold, and parametric modeling, with the capability of generating BRep when needed. Implicit modeling is used to represent overall part geometry, while nonmanifold modeling is used to represent shape skeletons. Parametric modeling is necessary when decomposing the overall part geometry into cellular structures; each cell type will be represented as a parametric model.

17.6.3.2 Implicit Modeling

Implicit modeling has many advantages over conventional BRep, CSG, cellular decomposition, and hybrid approaches, including its conciseness, ability to model with any analytic surface models, and its avoidance of complex geometric and topological representations [23]. The primary disadvantage is that an explicit boundary representation is not maintained, making visualization and other evaluations more difficult than with some representation types. For HSM, additional advantages are apparent. Implicit modeling offers a unified approach for representing geometry, materials, and distributions of any physical quantity. A common solution method can be used to solve for material compositions, analysis results (e.g., deflections, stresses, temperatures), and for spatial decompositions if they can be modeled as boundary value problems [24]. Furthermore, it provides a method for decomposing geometry and other properties to arbitrary resolutions which is useful for generating visualizations and manufacturing process plans.

In conventional CAD systems, parametric curves and surfaces are the primary geometric entities used in modeling typical engineered parts. For example, cubic curves are prevalent in geometric modeling; a typical 2D curve would be given by parametric equations such as

$$x(u) = au^3 + bu^2 + cu + d$$
$$y(u) = eu^3 + fu^2 + gu + h \tag{17.1}$$

These equations would have been simplified from their formulation as Bezier, b-spline, or NURBS (nonuniform, rational b-splines) curves [25]. In contrast, implicit functions are functions that are set equal to zero. Often, it is not possible to solve for one or more of the variables explicitly through algebraic manipulation. Rather, numerical methods must often be used to solve implicit equations. Frequently, sampling is used to visualize implicit functions or to solve them. More specifically, the general form of an implicit equation of three variables (assumed to be Cartesian coordinates) is presented along with the equation for a circle in implicit form:

$$z(x, y) = 0$$
$$z(x, y) = \frac{1}{2r}\left[(x - x_c)^2 + (y - y_c)^2 - r^2\right] \tag{17.2}$$

where x_c, y_c are the x and y coordinates of the circle center and r is its radius.

Shapiro and coworkers have advanced the application of the theory of R-functions to show how engineering analyses [24] and material composition [26] can be performed using implicit modeling approaches. The advantage of their approach is the unifying nature of implicit modeling to model geometry, material composition, and distributions of any physically meaningful quantity throughout a part. Furthermore, from these models of property distributions, they can perform analyses using methods akin to the Boundary Element Method (BEM).

As an example, consider the 2D rectangular part shown in Fig. 17.14 with rectangular and circular holes. The implicit equations that model the boundaries of the part are presented in (17.3a–17.3d). Equations (17.3a and 17.3b) models the x-extents and y-extents of the part, while (17.3c) and (17.3d) models the rectangular hole and (17.3e) models the circular hole ($r = 0.6$, $x_c = y_c = 0.1$). Note that the equation for each boundary feature is 0-valued at the boundary, is positive in the part interior, and is negative in the part exterior. These equations were formulated using R-functions [26].

$$w_1(x) = \frac{4 - x^2}{4} \tag{17.3a}$$

$$w_2(y) = \frac{8 + 2y - y^2}{9} \tag{17.3b}$$

$$w_3(x) = x^2 - 0.25 \tag{17.3c}$$

$$w_4(y) = 2(y - 3)^2 - 0.125 \tag{17.3d}$$

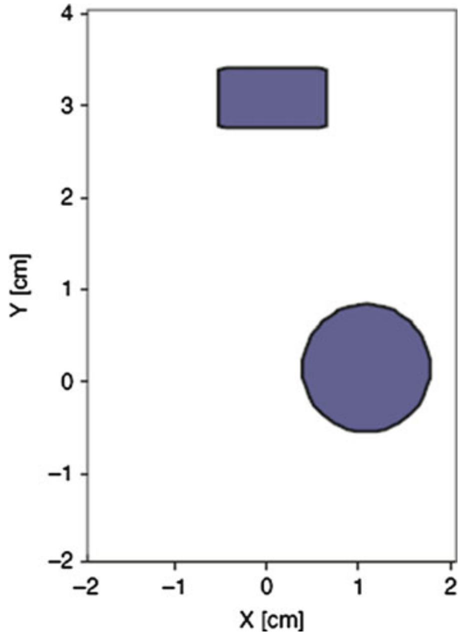

Fig. 17.14 Example part to illustrate implicit modeling

$$w_5(x, y) = \frac{1}{2r^2}\left[(x - x_c)^2 + (y - y_c)^2 - r^2\right] \tag{17.3e}$$

An equation for the entire part can be developed by combining the boundary functions using operators $\wedge$ and $\vee$ which, in the simplest case, are functions “min” and “max,” respectively; other more sophisticated expressions can be used. The part equation is

$$\mathbf{W} = w_1 \wedge w_2 \wedge (w_3 \vee w_4) \wedge w_5 \tag{17.4}$$

with the interpretation that the part is defined as Ω when $\mathbf{W}$ is greater than or equal to 0, $\boldsymbol{\Omega} = (\mathbf{W}(x, y) \geq 0)$

A plot of the part function is shown in Fig. 17.15, which shows contours of constant function value (17.4). Generalizing from the example, it is always the case that a single algebraic equation can be derived to represent a part using implicit geometry, regardless of the part complexity.

Additional, more sophisticated techniques can be applied to generate useful parameterizations of part models for modeling multiple materials or for applications in design, analysis, or manufacturing, but they will not be explored further here.

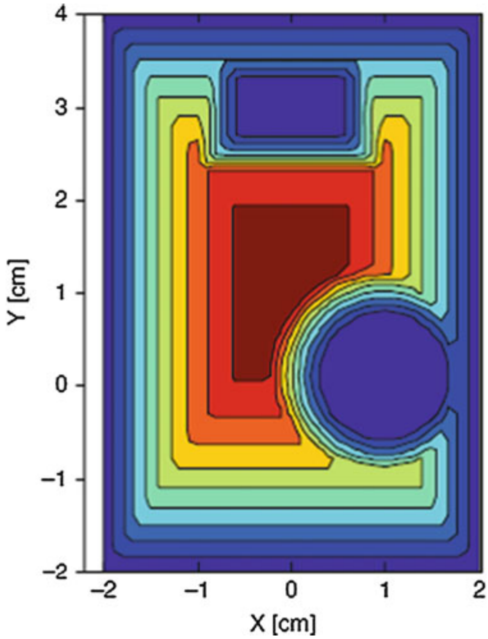

Fig. 17.15 Contours of implicit part equation

17.7 Synthesis Methods

The capabilities of AM processes have inspired many people to try to design structures so that they have minimum weight, without regard to geometric complexity. Quite a few researchers are investigating methods for synthesizing light weight structures, with the intention of fabricating the resulting structures using AM. The work has been extended in some cases to the design of compliant mechanisms, that is, one-piece structures that move. In this section, we provide a brief survey of some recent research in this area. A brief exploration of optimization methods will be covered, with an emphasis on the emerging area of topology optimization that promises to aid designers in efficiently exploring novel structures.

17.7.1 Theoretically Optimal Lightweight Structures

Several years ago, researchers rediscovered the pioneering work of AGM Michell in the early 1900s who developed the mathematical conditions under which structure weight becomes minimized [27]. He proved that structures can have minimum weight if their members are purely tension-compression members (i.e., are trusses) and derived the rules for truss layout. A typical Michell truss is shown in Fig. 17.16 for a common loaded plate structural problem. Note that the solution has a "wagon wheel" structure.

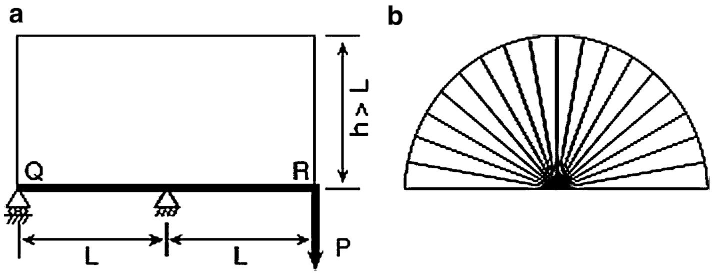

Fig. 17.16 Michell truss layout (**b**) for simple loaded plate example (**a**)

In general, it is difficult to compute optimal Michell truss layouts for any but the simplest 2D cases. Some researchers have developed numerical procedures for computing approximate solutions. At least one research group has proposed to fabricate Michell trusses using AM processes and has investigated multiple material solution cases [28]. For proposed synthesis algorithms for large complex problems, Michell trusses provide an excellent baseline against which solutions for more complicated problems can be compared.

17.7.2 Optimization Methods

In our context, optimization methods seek to improve the design of an artifact by adjusting values of design variables in order to achieve desired objectives, typically related to structural performance or weight, as well as possible without violating constraints. A variety of optimization problem formulations has been developed that vary based on type of objectives and scope of the problem. Good textbooks [29] and many research papers have been written on the subject. The three main types of optimization problems that have been explored for design for AM include, in order of increasing complexity and scope:

- Size optimization—where values of dimensions are determined
- Shape optimization—where shapes of part surfaces are changed
- Topology optimization—where distributions of material are explored

In size optimization, the values of selected dimensions are determined that best achieve the objectives while satisfying any constraints. For typical structural optimization applications, objectives could include the minimization of maximum stress, strain energy, deflection, or part volume or weight. One or more of these quantities may also be modeled as constraints. For many mechanical parts, a small number of size dimensions will be part of the optimization problem. However, for cellular structures, such as lattices, the number of design variables could number in the tens or hundreds of thousands.

Shape optimization is a generalization of size optimization. Typically the shape of bounding curves or surfaces is optimized to achieve similar objectives and constraints. As such, the positions of control vertices for curves or surfaces are often used as the design variables. Shape and size optimization are frequently combined in order to optimize structures that have free-form shapes, as well as standard shapes (e.g., cylinders) with dimensions.

In topology optimization, the overall shape, arrangement of shape elements, and connectivity of the design domain are determined. Again, part volume or compliance is minimized, subject to constraints on, for example, volume, compliance, stress, strain energy, and possibly additional considerations. The primary differences between topology optimization and shape or size optimization are in the starting geometric configuration and the choice of variables, which can lead to very significant improvements in structural performance. The recent interest in topology optimization as a design method for AM warrants a closer look into this technology.

17.7.3 Topology Optimization

Topology optimization (TO) methods determine the overall configuration of shape elements in a design problem. Often, TO results are used as inputs to subsequent size or shape optimization problems. As structural optimization methods, finite element analyses are performed typically during each iteration of the optimization method, which means that TO can be computationally demanding. Furthermore, TO solutions should result in structures that are nearly fully stressed, or have constant strain energy, throughout the structure geometry based on the specified loading conditions. Two main approaches have been developed for TO problems: truss-based and volume-based density methods.

17.7.3.1 Truss-Based Methods

In the truss-based approach, a mesh of struts among a set of nodes is defined in a volume of interest, where sometimes the mesh represents a complete graph (e.g., ground truss) and sometimes it is based on unit cells. Topology optimization proceeds to identify which struts are most important for the problem, determine their size (e.g., diameter), and remove struts with small sizes. Result quality is often a strong function of the starting mesh of struts. Results will resemble the lattice structures presented earlier, with variations in strut diameters evident.

In the first variations of truss-based methods, a ground truss was defined over a grid of nodes, with each node connected to every other node by a truss element. Each element's diameter was used as the design variable. As optimization proceeds, those elements whose diameters become small are deleted from the design. Although the methods worked well, they tended to be computationally expensive. Recently, more sophisticated methods have been developed that utilize a different problem formulation, involving background meshes and analytical derivatives for computation of sensitivities, for truss optimization methods [30]. Good results have

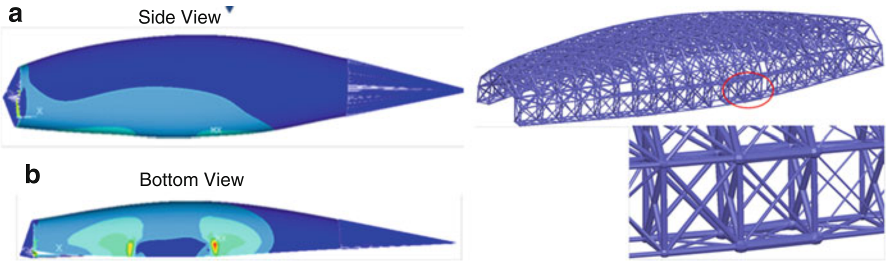

Fig. 17.17 SMS method results on UAV fuselage design problem

been achieved when both truss element size and position are used as design variables. Variations of these approaches have demonstrated the capability of achieving risk-based or reliability-related objectives [31].

Other synthesis methods utilize heuristic optimization methods in an attempt to greatly reduce the number of design variables in the optimization problem. For example, the Size Matching and Scaling (SMS) method starts with a conformal lattice structure (Sect. 17.5.2) but only requires two design variables, the minimum and maximum strut diameters, to optimize the structure [18]. The method works by performing a finite element analysis (FEA) on a solid body of the design. A conformal lattice structure is constructed that fits within the solid body. Local strain or stress values from the FEA results are used to scale struts in the lattice structure resulting in a set of relative strut size values. Size optimization is performed on the lattice structure to determine the values of the minimum and maximum strut diameters, using frame elements to model the lattice structure. Application of the SMS method to a simplified UAV fuselage design problem is illustrated in Fig. 17.17. Note that regions of high stress result in thick struts.

17.7.3.2 Volume-Based Density Methods

The second main approach is based on determining the appropriate material density in a set of voxels that comprise a spatial domain. The density-based TO method that is most common, and is used in the commercial software packages, is known as the SIMP (Solid Isotropic Material with Penalization) method. The starting geometry for the problem is a rectilinear block that is composed of a set of voxels. Each voxel has a density value which is used as its design variable. A density value of 1 indicates that the material is fully dense, while a value of 0 indicates that no material is present. Intermediate values indicate that the material need not be fully solid to support the local stress state in that voxel. Solutions are preferred that have voxels that are either fully dense or near 0 density, since typically partially dense materials are difficult to manufacture. Density values are used to scale voxel stiffness values in the FEA models that are used during the TO process.

The typical topology optimization problem is formulated as [32]:

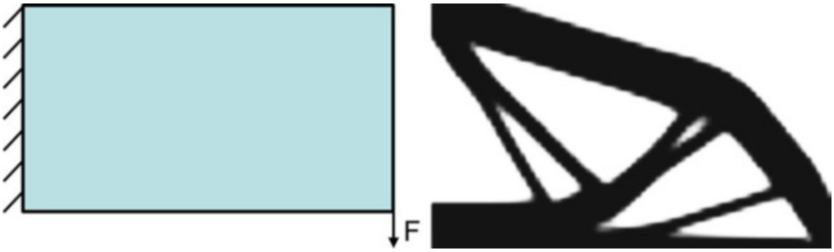

Fig. 17.18 Simple topology optimization example

$$\min_x L(u) = \int_\Omega \boldsymbol{f} \cdot \boldsymbol{v} dx + \int_\Gamma \boldsymbol{t} \cdot \boldsymbol{v}\, ds \tag{17.5}$$

such that

$$a(u, v) = L(v), \quad \text{all } v \in U \tag{17.6}$$

where

$$a(u, v) = \int_\Omega E_{ijkl} \varepsilon_{kl}(u) \varepsilon_{ij}(v) dx \tag{17.7}$$

x are points in the spatial domain of interest, U are admissible displacement fields, $\boldsymbol{f}$ are body forces, $\boldsymbol{t}$ are surface tractions. Equation (17.7) is known as the energy bilinear form. The design variables in this formulation are the elasticity tensors E_{ijkl}. In the SIMP method, the elasticity tensors are functions of density and sometimes orientation.

A typical example of topology optimization is shown in Fig. 17.18, which is a simple cantilever plate with a downward point load on its right side. Topology optimization algorithms can maintain the connectivity of material around the loading and boundary areas, and also ensure that these areas are connected. They can add an arbitrary number of holes or strut regions to the design domain. However, they often produce rough or undesirable part shapes. Although the design in Fig. 17.18 could be fabricated using AM, one would probably prefer smoother shapes and transitions between major shape elements. The example was computed using the popular 99-line TO Matlab code from Ole Sigmund [33], with inputs of 80×50 units in size, a volume fraction of 0.5, a penalization exponent of 3, and the rmin (filter size) term of 1.5.

Two popular commercial codes for TO are OptiStruct from Altair and Abaqus, which is marketed by Dassault Systemes. Both packages can solve a variety of TO problems. For example, OptiStruct provides 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. As a result, both composite shells (layout of laminated construction by modifying ply thickness and angle) and mechanisms can be optimized.

Before describing each package in more detail, the general limitations of these commercial TO systems will be highlighted. First, topology optimization is based on approximate models of mechanics that can differ substantially from the actual part or material mechanics. Furthermore, the simple mechanics models are inadequate for cellular materials since their mechanics cannot be approximated by an isotropic solid. For example, assume that an element has a density of 30 % and the designer wants to use the octet truss construction in the region of that element. Placing an octet truss unit cell into the 30 % solid region will result in completely different mechanical behavior than the behavior assumed during topology optimization.

Second, the results of topology optimization are rarely manufacturable directly, even by AM. Typically, designs retain their meshed surfaces so that they are rougher (and tessellated) than would be desired. Part regions may become very thin between thick sections, introducing unwanted stress concentrations. Some topology optimization systems do a better job of producing designs with smoother surfaces (e.g., ABAQUS), but even so the user manuals typically recommend that topology optimization results be used to guide part design—they provide conceptual solutions—rather than be regarded as suitable for production usage. Furthermore, the models produced by topology optimization are typically not suitable for import back into a CAD system for refinement since they will be facetted (original CAD surfaces have been lost) and will not have any parameters associated with geometric shapes. As such, it is very difficult to modify or refine topology optimization models in CAD.

Abaqus is part of the Simulia brand of CAE software marketed by Dassault Systemes. Abaqus is generally considered an excellent FEA package with state-of-the-art nonlinear and plasticity analysis capabilities. Multi-physics simulation is provided with integration between structural, thermal, fluid flow, and other mechanics models. Additionally, Abaqus has an extensive library of material models that includes metals, polymers, rubbers, and even biological tissues. A wide array of physical properties is included, including standard mechanical, thermal, fluidic, acoustic, and diffusion, as well as user-defined materials.

The Abaqus Topology Optimization Module (ATOM) offers topology and shape optimization capabilities that utilize much of the simulation power of Abaqus. Specifically, topology and shape optimization is offered for single parts and assemblies, while leveraging advanced simulation capabilities such as contact, material nonlinearity, and large deformation.

The second commercial system to be discussed is from Altair, which offers their HyperWorks suite of CAE software that includes OptiStruct, their topology optimization package. More generally, OptiStruct is marketed as a structural analysis solver for linear and nonlinear structural problems under static or dynamic loadings. Structures can be optimized for their strength, durability, NVH (noise-vibration-harshness), thermal, and some acoustics characteristics. Altair claims that OptiStruct can solve optimization problems with thousands of design variables

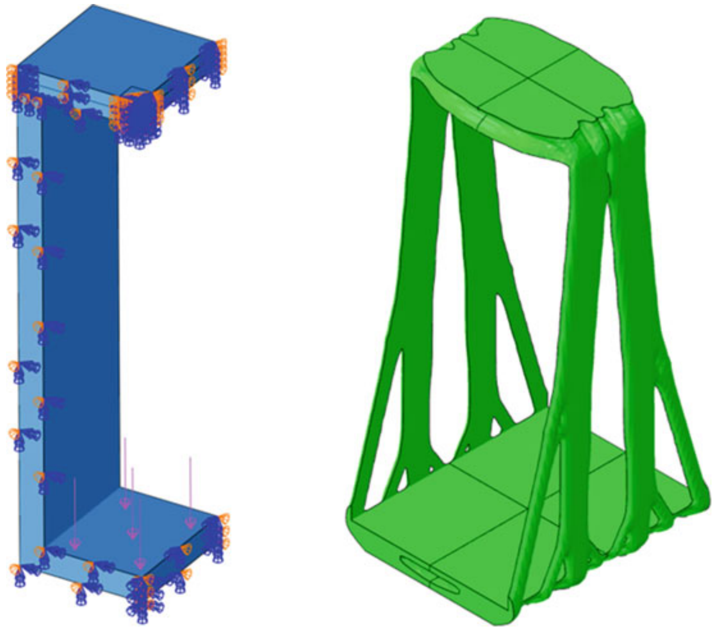

Fig. 17.19 3D cargo sling topology optimization example. Courtesy Mahmoud Alzahrani and Dr. Seung-Kyum Choi, Georgia Institute of Technology

and can combine topology, topography (e.g., vary thickness of a sheet), size, and shape optimization capabilities. Additionally, the composites models that can be generated in HyperMesh can be optimized in OptiStruct. Further, OptiStruct can optimize both flexible and rigid bodies during multi-body dynamic analysis. Fatigue-based concept design and optimization is also provided.

Also from Altair, solidThinking Inspire is a separate application that supports easy-to-use topology optimization capabilities. solidThinking is the name of the company that developed the software; they were acquired by Altair recently (2012–2013). From the company literature, Inspire does not seem to be integrated with HyperWorks or OptiStruct, but it should be only a matter of time before some integration is achieved.

As a second example, a more sophisticated 3D TO problem is shown in Fig. 17.19, which represents a cargo sling design problem. The design domain, shown in the left, is $3 \times 3 \times 6$ m in size with a material thickness of 0.3 m (a quarter model was used to take advantage of symmetry). A pressure load of 3 kPa was applied as shown by the arrows. Symmetry boundary conditions were used. The TO solution was computed in Abaqus for a volume constraint of 15 % of the initial volume in the design region, as shown on the right. The example demonstrates that reasonable solutions can be obtained using commercial TO systems in a reasonable amount of time (1 h on a standard PC).

TO remains a very active topic of research. Some of the research issues and directions under investigation include ensuring connectivity of regions in the resulting structures [34], improving the efficiency of TO methods by introducing the concept of a topological sensitivity [35], and exploring alternative solution approaches such as level sets and evolutionary structural optimization. The level set approach [36] models the distribution of material in a domain using an implicit function representation. The part boundaries are computed by finding the zero-level contour of this implicit function representation. Quite a lot of research is underway to develop efficient, robust level set solution algorithms, particularly for 3D problems. In contrast, evolutionary structural optimization methods [34] utilize stochastic, evolutionary optimization methods, such as genetic algorithms and particle swarm optimization, but with a problem formulation that is similar to SIMP. In these methods, typically elements are removed or added based on the sensitivity of an element or node as measured by the change in the structure's mean compliance of removing that element or node.

17.8 Summary

The unique capabilities of AM technologies enable new opportunities for designers to explore new methods for customizing products, improving product performance, cutting manufacturing and assembly costs, and in general developing new ways to conceptualize products. In this chapter, we compared traditional DFM approaches to DFAM. AM enables tremendous improvements in many of the considerations that are important to DFM due to the capabilities of shape, hierarchical, functional, and material complexity. Through a series of examples, new concepts enabled by AM were presented that illustrate various methods of exploring design freedoms. No doubt, many new concepts will be developed in future years. Challenges and potential methods for new CAD tools were presented to overcome the limitations of traditional parametric, solid-modeling CAD systems. A brief overview of optimization methods was given to illustrate some automated synthesis methods for designing complex structures. Several examples were given to illustrate the types of solutions that can be generated; the resulting geometries are complex enough to preclude fabrication using conventional manufacturing processes.

This chapter covered a snapshot of design concepts, examples, and research results in the broad area of DFAM. In future years, a much wider variety of concepts should emerge that lead to revolutionary ways of conceiving and developing products.

17.9 Exercises

1.–4. Describe in your own words the four AM unique design capabilities described in this chapter and give one example of a product that could be improved by the proper application of each design capability. The example products cannot be ones that were mentioned in this book.

5. What are three ways that current designers are trained that are at odds with the concept of DFAM?
6. Why is optimization a more challenging issue with DFAM than for DFM?
7. For one of the products identified in problems 1–4, draw in CAD the original design and your redesign based upon the application of DFAM principles.

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