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A Survey of the Design Methods for Additive Manufacturing to Improve Functional Performance

Abstract

Purpose

To provide a comprehensive review of the state of the art design methods for additive manufacturing technologies to improve functional performance.

Methodology/approach

In this survey, design methods for additive manufacturing to improve functional performance are divided into two main groups. They are design methods for a specific objective and general design methods. Design methods in the first group primarily focus on the improvement of functional performance, while the second group also takes other important factors such as manufacturability and cost into consideration with a more general framework. Design methods in each group are carefully reviewed with discussion and comparison.

Findings

The advantages and disadvantages of different design methods for additive manufacturing are discussed in this paper. Some general issues of existing methods are summarized below:

- 1 Most existing design methods only focus on a single design scale with a single function.
- 2 Few product-level design methods are available for both products' functionality and assembly.
- 3 Some existing design methods are hardly to implement for the lack of suitable computer-aided design software.

Practical implications

A useful source for designers to select an appropriate design method to take full advantage of additive manufacturing.

Originality/value

In this survey, a novel classification method is used to categorize existing design methods for additive manufacturing. Based on this classification method, a comprehensive review is provided in this paper as an informative source for designers and researchers working in this field.

Keywords:

Design methods, additive manufacturing, functional performance, manufacturability, cellular structure

1 Introduction

Additive Manufacturing (AM) is defined as a material joining process whereby a product can be directly fabricated from its 3D model (ASTM, 2012). Compared to other manufacturing methods, such as machining or casting, AM processes have the following unique capabilities. Firstly, parts with extremely complex shape can be built by AM processes without increasing fabrication cost. Secondly, AM technologies are suitable for processing multiple materials either simultaneously or sequentially; therefore, parts with complex material compositions can be fabricated by this

manufacturing method. Thirdly, manufacturing preparation time can be substantially reduced, since the part is directly fabricated from its 3D model. These unique capabilities of AM technologies have brought great application potentials in several major industries such as aerospace (Angrish, 2014) and medical implants manufacturers (Jardini et al., 2014). For example, in the aerospace industry, lightweight, strong and sometimes electrically conductive parts are more desired. AM process can produce lightweight components by replacing solid material with lattice structures. Gradient electrical conductivity can also be achieved by changing the composition of materials at each fabrication point or each fabrication layer. Major airplane manufacturers such as Boeing, Airbus, and Northrop Grumman have all identified AM to be an emerging and revolutionary manufacturing method (Bourell et al., 2009).

However, it is also a challenge for most designers to take full use of the unique capabilities brought by AM for two main reasons. Firstly, design rules or guidelines for traditional manufacturing methods are deeply rooted in designers' mind. These design rules and guidelines restrict designers to further improve the performance of products by designing an intricate part fabricated by AM processes. Secondly, lack of design and analysis tool for complex structure is another obstacle for designers to take full use of AM technologies. For example, even though the lattice structure fabricated by AM process has been proved to have a better weight-stiffness ratio, it is difficult to model this type of structure with most existing featured-based CAD systems.

In order to overcome those difficulties mentioned above, the design methods to consider the unique capabilities of AM technologies are needed. These design methods are not only required to improve the manufacturability of products fabricated by AM processes, but also should consider how to improve the overall functional performance of designed products with the unique capabilities brought by AM. To achieve the above objectives, in this paper, a concept called as Design for Additive Manufacturing (DFAM) is proposed.

“Design for Additive Manufacturing is a type of design methods whereby functional performance and /or other key product life-cycle considerations such as manufacturability, reliability and cost can be optimized subjected to the capabilities of additive manufacturing technologies.”

This concept provides a broader perspective of design methods which can take use of AM technologies during a design process. It has intersections between many traditional DFX methodologies such as Design for Manufacturing, Design for Maintenance and Design for Cost. However, unlike most traditional Design for Manufacturing and Cost methods which mainly aim at tailoring designs to minimize manufacturing difficulties and cost, DFAM also provides opportunities for designers to take the unique capabilities of AM technologies in the design process to improve functional performance without decreasing manufacturability and increasing cost. To emphasize this unique opportunity brought by AM technologies, this survey paper will mainly focus on those DFAM methods for the improvement of functional performance. Thus, in this paper, unless otherwise specified, the narrow perspective of DFAM is used to indicate those DFAM used for the improvement of functional performance. Actually, some of DFAM methods have already been employed in several different fields. For example, in the aerospace industry, topology optimization, one of the DFAM methods, serves to reduce the weight of products and increase their stiffness. Complex optimized shapes of products can only be fabricated by AM

techniques. In bioengineering, the bio-implant with meso-level structure can be designed by DFAM methods. This type of bio-implant can achieve the same mechanical properties of real human bone, which can avoid stress shielding after surgery. Due to its wide application, DFAM has recently attracted a great interest from different application fields.

This paper is an attempt to provide a comprehensive review of the state of the art DFAM methods for the designers who want to take advantages of AM technologies to further improve the products' performance, as well as the researchers who aim to develop some innovative DFAM methods. To achieve this goal, existing DFAM methods are classified into two main groups: DFAM methods for functional performance and general DFAM methods (shown in Figure 1). The first group of design methods primarily focuses on the specific objective that is functional performance. Thus, this group of DFAM methods is also called as objective specific DFAM methods in this paper. In this review paper, objective specific DFAM methods are further divided into three sub-groups according to its design scale. It will be separately discussed in the Section 2. Compared to the objective specific DFAM methods, general DFAM methods are able to provide a general design flow which can consider several design objectives simultaneously. This type of DFAM methods will be discussed in the Section 3. Finally, this paper is wrapped up with a conclusion and some prospects for the future research.

Figure 1 the classification of DFAM methods for functional improvements

2 DFAM methods for functional improvements

In this section, objective specific DFAM methods which mainly focus on functional improvements are discussed. These design methods are divided into three groups according to their relative design scales. Design methods deal with feature sizes between 0.1 and 10mm are considered as mesoscale. Those design methods which focus on the larger features than mesoscale are counted as macroscale, and the design methods which deal with the smaller features than mesoscale are classified as microscale. Typical feature of each design scale is shown in Figure 2. These three groups of design methods will be discussed respectively in the next three sub-sections.

(a) Macroscale

(b) Mesoscale

(c) Microscale (Ram et al., 2007)

Figure 2 design features in different design scales

2.1 Macroscale design

On a macroscale, structural optimization are the most commonly used methods for structural parts which are intended to sustain loads. Generally, these structural optimization methods can be divided into three categories. They are size optimization, shape optimization and topology optimization. Compared with other two structural optimization methods, topology optimization method does not only optimize the boundary shape of a part but also changes its topology, which can offer a better solution for certain requirements (Bendsøe, 2003). Thus, topology optimization

has received designers' extensive attention, especially in the conceptual design stage. Initially, topology optimization methods are proposed only to deal with the structural design. However, now this type of optimization methods has spread to a wide range of disciplines, including fluid (Borrvall and Petersson, 2003), acoustic (Dühring et al., 2008), control (Deng et al., 2013b), optics (Frandsen et al., 2004). Several different topology optimization methods including ground structure method (Bendsøe et al., 1994, Dorn et al., 1964), homogenization method (Bendsøe and Kikuchi, 1988), Solid Isotropic Material with Penalization (SIMP) method (Rozvany et al., 1992), level set method (Allaire et al., 2002, Wang et al., 2003), evolutionary method (Xie and Steven, 1993, Young et al., 1999) and genetic method (Wang and Tai, 2005, Chen et al., 2009) have been proposed to optimize parts' topology. In order to improve parts' performance, different topology optimization methods are used in different applications. For the detailed introduction and discussion between different types of topology optimization methods, readers can further refer some recently published review papers on topology optimization (Brackett et al., 2011b, Rozvany, 2009). In this paper, we focus on those topology optimization methods which have been applied to design the parts fabricated by AM processes. A brief comparison between these methods is summarized and shown in Table 1. From this table, it is clear that ground structure method is the most suitable approach for macro truss like structure. Based on the ground structure method, the macro-lattice is designed by Navasivayam and Seepersad (Namasivayam and Seepersad, 2011) to decrease the deviation from intending surface profile of UAV wing. The optimized structure has been successfully fabricated by Selective Laser Sintering (SLS) process. Based on the interpolation scheme, Lin and et al. (Lin et al., 2010b) take use of SIMP method to design adaptive cores of the structure for a uniform beam which is capable of large deflection while simultaneously processing load carrying capabilities. Another SIMP based method has recently proposed by Gaynor et al (Gaynor et al., 2014) to design multi-material compliant mechanisms fabricated via PolyJet technique. In this design method, the SIMP approach is modified by combination with a combinatorial SIMP approach and multiphase SIMP approach to design the multi-material topology for compliant mechanisms. Besides SIMP, Bidirectional Evolutionary Structural Optimization (BESO) method is used by Aremu and et al. (Aremu et al., 2013) to optimize an aerospace component. This research shows evolutionary optimization methods can steer the solution to an optimum with features suitable for AM process by careful selection of a suitable set of optimization parameters. More recently, some topology optimization based design methods have been proposed to further consider the manufacturing capability of some AM processes. For example, Leary et al. (Leary et al., 2014) has proposed a design method to seek the optimal topology of designed parts fabricated by those support needed AM processes. In this design method, the theoretically optimal topology is modified to ensure manufacturability without requiring additional support material. Another topology optimization based design method is proposed by Gardan and Schneider (Gardan and Schneider, 2014) to seek the optimized internal pattern fabricated by Selective Laser Sintering (SLS) process. Manufacturing constraints and considerations generated from the knowledge management of SLS process are integrated into the optimization process. Moreover, some pre-designed cleaning channels are added to the final optimized result to ensure the powders cleaning inside the internal cavity. It is obvious that most existing topology optimization based design methods on a macro level only focus on the improvement of a single function such as structural stiffness. However, recently

some research has been conducted to further extend topology optimization to design parts with multiple function. Brackett et al. (Brackett et al., 2013) has proposed a topology optimization based design framework for multi-functional 3D printing. In this design framework, the automated placement and routing of electrical systems are integrated into the topology optimization process for Structural Health Monitoring (SHM) product. This framework has recently been extend to 3-dimentional design by Panesar et al.(Panesar et al., 2014).

Besides those academic efforts mentioned above, some commercial software like OptiStruct (OptiStruct) have been developed to help designers with less knowledge and experience on structural optimization. These software have been successfully applied to optimize the parts fabricated by AM processes (Chang and Tang, 2001, Lynch et al., 2013). However, more developing work should be done for those commercial software to integrate the unique manufacturing capabilities of AM in the structural optimization process. Moreover, the multifunctional performance should also be considered in their future version.

Table 1 Advantages and Disadvantages of different type of topology optimization method

Another notable type of DFAM methods on a macroscale is the design of customized products. This type of DFAM methods has a wide application on customized medical devices and personal products. Compared to standard medical devices, customized devices not only can satisfy the needs of the patients who are outside the standard range with respect to implant size or diseases-specific special requirements, but also provides an individual fitting and adequate match which will further improve the surgical outcome (Rengier et al., 2010). The general design and manufacturing flow of customized medical devices is summarized and shown in Figure 3. This general flow mainly consists of five steps: image acquisition, image post-processing, surgical planning, customized devices design and AM fabrication. Now several customized prostheses, such as cranial bone (Chulvi et al., 2013, D'Urso et al., 2000, Singare et al., 2007), hip joint (Dai et al., 2007) and femoral joint (Faur et al., 2013), have already been successfully designed and fabricated. The results of these successful cases foresee the brilliant future of customized medical devices fabricated via AM processes. Besides customized medical devices, some consumer goods, such as customized shoes (Xiong et al., 2010), are also successfully designed to address the individual requirements of customers. These customized products can further improve user experience compared to their original designs.

Besides those successful cases of customized products mentioned above, several research has been recently done to further facilitate the efficiency of current customized design process for AM technologies. For example, a template based design method for customized products is proposed by Ariadi and Rennie (Ariadi and Rennie, 2008). In this design method, a product template provided by Product Family Architecture (PFA) is generated to allow consumers to develop a customized product. An investigation has been done by Ariadi et al (Ariadi et al., 2012) to further study the potential for consumers designing their own products. The result of this investigation shows the possibility that consumers can be involved in the design procedure of customized products. Moreover, the result of this research also suggests that a careful attention must be paid to consumers' product preferences and their ability to use software. A specific CAD

tool for computer mice is developed by Zhou (Zhou et al., 2010b). In this design tool, a co-design method is used to enable customers to decide the size and shape of mouse. In order to establish a connection between customization design for AM and software product line (SPL) engineering, an exploratory study (Acher et al., 2014) has been done on the popular 3D printing customization website called “Thingiverse”. This research provides hints that SPL-alike techniques can be also used in the design process of customized products fabricated by AM processes. To summarize current research on DFAM methods for product customization, it is clear that besides some specific design cases, most studies are focusing on co-design methods which enable customers to participate in a design process. However, how to share the design knowledge and information between designers and customers is still an issue for this type of design methods. Moreover, the role of surgeon or other people with specialized knowledge is also needed to consider in the design process of customized products.

Figure 3 General design and manufacturing flow of customized medical device

2.2 Mesoscale design

On a mesoscale, cellular structures are widely used to achieve an excellent performance and multi-capabilities while reducing weight. The word ‘cell’ derives from the Latin *cella* which means a small room (Merriam-Webster., 2004). Cellular structure can be regarded as a kind of structure that consists of an interconnected network of solid struts or plates which form the edges and faces of cells (Gibson and Ashby, 1999). This kind of structure is common in nature, such as wood, bone and coral which are able to bear a long-term static or cyclical load. These natural cellular structures have been used by humans for centuries. Recently, some man-made cellular structures have been designed and fabricated for their multi-functionalities such as weight reduction, energy absorption, heat transfer, thermal protection and insulation (Evans et al., 2001, Gibson and Ashby, 1999, Gibson, 2005, Varanasi et al., 2013, Hosseini et al., 2014).

In this section, several classification methods for cellular structures are firstly discussed. Then the state of the art design methods for lattice structure, one of the most widely used cellular structure, are reviewed.

2.2.1 Classification of Cellular Structure

In order to help designers to select a suitable type of cellular structure on a mesoscale, three different classification methods have been taken to divide cellular structures into different groups. The different properties of the cellular structures from different groups will be discussed.

Firstly, according to the geometric configuration of each cellular unit, cellular structures can be classified into foam structure (Figure 4), 2-dimensional lattice structure (Figure 5) also called as honeycomb structure and 3-dimensional lattice structure (Figure 6). Foam structure is formed by trapping a pocket of gas in solid. One of the most important divisions of foam structures is whether it is closed-cell foam (Figure4a) or open-cell foam (Figure4b). For closed-cell foams, the gas pocket in each cellular unit is completely separated by solid walls. While, for open-cell foams, the gas pockets are connected to each other. Besides foam structures, honeycomb structure is another type of cellular structures which have been widely used in the aerospace

industry. Sometimes, honeycomb structure is also called as 2-dimensional cellular structure, since this kind of cellular structure is composed of two-dimensional cells which have been extruded in the third direction to fill the three-dimensional space. Honeycomb structures are always used as the core of a sandwich panel, which can provide the panel with minimal weight and relatively high out-of-plane compression properties and out-of-plane shear properties (Wahl et al., 2012). Recently, another kind of cellular structure called 3-dimensional lattice structure has received considerable research attention. This kind of structure is a space truss structure which is composed of struts, nodes and other micro-element with certain repeated arrangement in three dimensional space.

Figure 4 Example of disordered foam structure(Gibson and Ashby, 1999)

Figure 5 Example of 2-dimensional lattice structure

Figure 6 Example of 3-D lattice structure (Wadley et al., 2003)

Another classification method for cellular structures is based on its degree of order. Generally, this classification approach can divide cellular structures into three types. The first type is called disordered cellular structure. Cell units with different size and shapes are randomly distributed inside the design space, such as the foam structure shown in Figure 4. Most foam structures belong to this type. Due to its stochastic characteristics, large portion of structures is required to study its physical properties. The second type of cellular structure is called periodic cellular structure. This type of cellular structures can be regarded as three dimensional structure created by a regular repetition of an object with certain shape, topology and size in either plane or space. In some literatures (Wang, 2005, Chang and Rosen, 2012, Chang and Rosen, 2013), this type of structures is also called as uniform cellular structure. Most 2-dimensional and 3-dimensional lattice structures belong to this type. Unlike disordered cellular structure, only a unit cell which is a small portion of periodic cellular structure is needed to determine its physical properties. Thus, the topology of a unit cell plays a key role in the properties of this kind of cellular structure. Some common unit cell topologies considered in literatures are summarized in Table 2. Periodic cellular structure can be further divided into two types. If all unit cells in structure share exact same geometry, this kind of periodic cellular structure can be called as homogeneous periodic cellular structure. Otherwise, those structures whose cells only share the same topology and size with different thickness of struts are called heterogeneous periodic cellular structure. The difference between these two kinds of periodic cellular structure is shown in Figure 7. Besides disordered cellular structure and periodic cellular structure, another type of cellular structure is called pseudo-periodic cellular structure shown in Figure 8. In this type of cellular structure, unit cells only share the same topology but different shape and size. For example, the conformal lattice structure proposed by Rosen's research group (Wang and Rosen, 2002) is a typical pseudo-periodic cellular structure. In the conformal lattice structure, the shape and size of each unit lattice cell vary according to part's macro geometry.

Table 2 Common cell topologies

(a) Heterogeneous lattice

(b) Homogenous lattice

Figure 7 Difference between heterogeneous lattice and homogeneous lattice

(a) Periodic lattice structure

(b) Pseudo-periodic lattice structure

Figure 8 Difference between periodic lattice and pseudo-periodic lattice

Based on deformation mechanism, cellular structure can be divided into bending dominated structure and stretching dominated structure. A topological criteria has been investigated by Deshpande, Ashby and et al. (Deshpande et al., 2001) to derive the deformation mechanism of a cellular solid by analyzing the rigidity of pin-jointed frameworks comprising inextensible struts. In their research work, a generalization of a Maxwell rule (Calladine, 1978) in three dimensional truss structure is used. This rule can be expressed as:

$$b - 3j + 6 = s - m \quad (1)$$

Where b is the number of struts in the structure; j is the number of pin-joints; m and s count the states for self-stress and mechanism. The structure which is both static determinant and kinematic determinant has $s = m = 0$. For the stretching dominant structures, m must equal to zero, which means that the structure is fully static determinant. Different characteristics of deformation mechanism between bending and stretching dominated cellular structure can significantly affect its mechanical properties such as stiffness and strength. With the same relative density $\bar{\rho} = 0.1$, stretching dominated foam is expected to be about ten times as stiff and around three times as strong as bending dominated foam (Deshpande et al., 2001). Thus, for the place where light and stiffness parts are needed, such as aircraft structural parts, stretching dominated cellular structure is in favor. While for those products which are designed for energy absorption or compliant mechanism, bending dominated cellular structures are preferred.

Among many different types of cellular structures, lattice structures including both 2-dimensional and 3-dimensional lattice have received considerable attention from researchers due to their inherent advantages. Compared to cellular foam, lattice structures enable designers much more freedom to realize their design goals. On one hand, lattice structures can be designed to be a stretching dominated structure which is much more stiff and stronger than bending dominated foam structures. On the other hand, compliant mechanism can also be realized through bending dominated lattice structures. Thus, most DFAM methods on a mesoscale mainly focus on lattice structures.

2.2.2 Design methods for lattice structure on a mesoscale

As mentioned at the beginning of this section, compared to solid material, lattice structures on a mesoscale have many unique capabilities. Especially, there is no additional cost for designing and fabricating mesoscale lattice structures by AM processes. Thus, DFAM methods on a mesoscale have attracted researchers' great interest. In general, the proposed DFAM methods for lattice structures on a mesoscale can be classified into two different groups. They are DFAM methods for homogeneous lattice and DFAM methods for customized lattice structures. In the following paragraphs, basic concepts and recent research progress of these two groups of design methods are reviewed respectively.

DFAM methods for homogeneous lattice structure

For material scientists and engineering designers, homogeneous lattice structures on a mesoscale can be regarded as homogeneous materials on a macroscale. The effective properties of lattice structure on a macroscale can be calculated by several homogenization methods. Based on the calculated effective properties, the macro shape of homogeneous lattice structure can be designed by the macroscale design methods. On a mesoscale, material selection strategy (Ashby and Cebon, 1993) shown in Figure 9 can be applied to select an appropriate meso lattice topology with respect to design requirements. Besides directly selecting existing lattice topologies in a material chart, sometimes, designers can also design a lattice structure with new topology or shape on a meso or microscale to fill the blank area of material chart for some desired properties. The technique called as "inverse homogenization" is first proposed by Sigmund (Sigmund, 1994, Sigmund, 1995) to optimize material distribution in each unit cell for desired material properties. Based on pioneering works of Sigmund, various structural optimization techniques have been applied to design geometry of each unit cell on a meso or microscale. So far, three types of topology optimization methods including ground structure optimization method, SIMP and Bidirectional Evolutionary Structural Optimization method (BESO) have been successfully applied to design a lattice unit cell for desired mechanical properties (Sigmund, 1994, Sigmund, 1995, Neves et al., 2000, Almeida and da Silva Bártolo, 2010, Huang et al., 2011, Radman et al., 2013b). Besides mechanical properties, some computational or optimizing models are developed to design cell's topology and structure for other types of desired property, such as thermal conductivity (Zhou and Li, 2008a), electromagnetic property (Zhou et al., 2010a), or combination of several properties at the same time (Challis et al., 2008, Torquato et al., 2003, Guest and Prévost, 2006). Readers should be noted that the inverse homogenization technique will be also used for micro-cell design, which will be discussed at the next sub-section.

Figure 9 Strategy of material selection for design (Ashby and Cebon, 1993)

Besides directly using the design methods on a macroscale based on the homogenized macro properties, some design methods are proposed for specific weight efficient parts with meso-lattice core, such as sandwich panels and beams. Typical sandwich panel is made up of two stiff, strong skins separated by a lightweight core which is usually cellular structure (Gibson and Ashby, 1999). The lightweight core can increase structure's moment of inertia with little increasing its weight. Thus, this kind of structure is often used in the application where weight-saving is critical, such as the aerospace industry. Gibson and Ashby (Gibson and Ashby, 1999)

proposed a design method for sandwich panels with foam core based on a consideration of both stiffness and strength. In their design method, the core thickness, c , the face thickness, f , the core's density, ρ^* , are regarded as design variables. The objective of this design method is to minimize structure's weight while guarantee given stiffness and strength requirements. Three different types of failure modes are specifically discussed and a failure map is given. Same methodology has been used by Deshpande and Fleck (Deshpande and Fleck, 2001) to design and analyze the collapse of truss core sandwich with either solid face or triangulated face-sheets. By modeling triangular truss as pin-jointed assemblies, effective properties of triangular truss core and face are calculated. Based on the calculation result, a collapse mechanism map is generated. With this map, an optimization procedure can be performed graphically based on equations of failure modes for the faces and core. Then, the optimal sandwich beam of minimum weight for a given structural load index can be selected. The result of their research shows that sandwich beams with lattice cores are significantly lighter than competing concept with foam cores. Another weight minimization of sandwich panels with truss cores is proposed by Wicks and Hutchinson (Wicks and Hutchinson, 2001, Wicks and Hutchinson, 2004). In their design method, two different loading conditions: shear-bending and compression are considered with (Wicks and Hutchinson, 2004) or without (Wicks and Hutchinson, 2001) crushing stresses applied to the face. Instead of calculating effective properties of truss cores, the relationship between external load and stress in each structural member is established by analysis of the truss structure. This method assumes that the faces and core are made of the same material and design is only subjected to strength constraints based on four failure modes. Sequential Quadratic Programming (SQP) method is used to solve this optimization problem. The result of their method also shows that solid sheet faces and truss cores are highly efficient from a weight standpoint.

Another generalized closed form optimization procedure for sandwich structures with a truss core is proposed by Rathbun and et al (Rathbun et al., 2005). Compared to Wicks and Hutchinson's method, this method also takes minimum weight of sandwich panels as the design objective. However, instead of using optimization algorithm, design parameters are solved directly by three in-active strength constraints. Then the fourth strength constraint is used to check whether the previous solution is admissible. This method can deal with four types of lattice topologies: tetrahedral, pyramidal, square honeycomb and corrugated sheets. In order to design a structure in a complex loading environment, multi-objective and multi-loading optimization methods for sandwich panels with lattice core are presented by Liu and Lu (Liu and Lu, 2004). A systematic method based on the concept of parameter profiles is used to evaluate structure's overall performance under multi-loading conditions. With this evaluation method, multi-objectives of sandwich structure with lattice core, such as weight, maximum stress, and fundamental frequency can be optimized simultaneously. In order to reduce the computational load during an optimization process, the same authors proposes another optimization design method (Liu et al., 2006) for sandwich structure with lattice core. In this method, a homogenization method is used to calculate the effective properties of a lattice core. Compared with their previous method, the new method can significantly reduce the computational load and also takes cell's topology into consideration. Recently, another closed-form optimal design method is proposed by Dragoni (Dragoni, 2013). Design of the entire sandwich structure is decoupled into face design and core design. Based on established equations, the sandwich panel

design problem is formally defined as the search for the lightest core topology satisfying all the design constraints on core's thickness, allowable normal and shear strength and minimum Young's and shear moduli. Compared to other methods mentioned above, this design method is much easier for implementation and also can deal with sandwich structure whose core and face are made of different materials. Besides bearing load with lightweight, other functions such as active cooling, energy absorption, internal actuation can also be achieved by careful design sandwich's homogeneous lattice core (Wadley, 2006, Lu et al., 2005, Hutchinson et al., 2003). It is clear that except design methods proposed by Liu and Lu (Liu and Lu, 2004), most existing design methods for sandwich structures with a lattice core can only be used to design for one or two objectives in a single discipline.

Customized lattice design methods

To further improve the performance of a designed lattice structure, lattice strut's thickness and its frame can also be optimized. In this review paper, this type of optimized lattice structure is called as customized lattice structure. According to the classification method of lattice structure introduced above, customized lattice structure mainly includes two major types of lattice structures. They are heterogeneous lattice and pseudo-periodic lattice. Because of its high complexity, customized lattice structure can only be fabricated by AM techniques. Thus, design methods for this type of structure are typical DFAM methods. In the following two paragraphs, DFAM methods for two major types of customized lattice structures will be reviewed respectively.

The key design parameter of heterogeneous lattice structure is the distribution of strut's thickness in the design domain. In order to obtain the optimized distribution of strut's thickness. Several structural optimization methods can be applied to design heterogeneous lattice on a mesoscale. Among different structural optimization methods, the size optimization method can be directly applied to design heterogeneous lattice structure. In this design process, the thickness of each lattice strut is regarded as a design variable, and key performance indexes such as displacement or maximum Von-Mises stress can be regarded as design objectives. Compared to other design methods for heterogeneous lattice design, the size optimization method is the easiest one to implement, since there is no complex conversion between design requirements and optimization parameters. Although some standard programming methods can be applied to solve this optimization problem, a large number of design variables and a heavy computational load for direct analysis on a mesoscale make this method impractical. In order to reduce optimization parameters, topology optimization methods based on SIMP (Rezaie et al., 2013) or homogenization theory (Sundararajan, 2011) are proposed to design heterogeneous lattice structure. In Sundararajan's method, homogenization approach is first used to establish the relationship between the lattice unit cell's relative density and its mechanical properties. Based on this relationship, topology optimization method is used to obtain optimized relative density distribution in the design domain. The result of topology optimization can be directly converted to the thickness of lattice struts. Compared to size optimization method, the design variables can be reduced from $n \times m$ to n , where n is the number of unit cells in the whole structure and m is

the number of struts in each unit cell. Moreover, a macroscale analysis can be used to obtain the response of structures for this optimization method. Thus, a heavy computation load for size optimization can be avoided. Rezaie et al. (Rezaie et al., 2013) has proposed another design method for lattice structures based on topology optimization. Compared to Sundararajan's method, SIMP approach is used for topology optimization instead of the homogenization method. The lattice structure on a mesoscale is used to represent intermediate relative density from the result of topology optimization.

Compared to size optimization methods, topology optimization methods mentioned above shows great advantages. However, there are still some problems in the current heterogeneous lattice design methods. Firstly, none of the aforementioned design methods considers the effect of optimization parameters on the final design result. For example, in topology optimization for structural part, FEA method is usually used to calculate displacement response of the structure under a certain load. Different size or types of elements in FEA will lead to the different results for topology optimization. Thus, more research needs to be done on how to select parameters for topology optimization based on given lattice cell size and topology. Secondly, current design methods only consider simple design objectives and constraints. However, for some more complex design tasks, multiple design objectives and constraints should be considered. Thus, research on how to convert these complex multiple design objectives and constraints into topology optimization is necessary. Thirdly, almost all of current design methods are based on the assumption that thicknesses of struts in each unit cell are equal. However, no research has been done to show the lattice structure designed under this assumption is optimal. Thus, some further research should be done to find whether anisotropic lattice unit cell can achieve better structural performance.

Besides heterogeneous lattice structures mentioned above, another type of customized lattice structure called pseudo-periodic lattice structure has also attracted a lot of researchers' attention. Generally, design methods for pseudo-periodic lattice structure can be divided into two types. They are geometry conformal lattice and load adaptive lattice. The concept and design method of geometry conformal lattice is first proposed by Wang and Rosen (Wang and Rosen, 2001, Wang and Rosen, 2002, Wang, 2005). The difference between conformal lattice and uniform lattice is shown in Figure 7. It is manifested that the shape of each unit cell is no longer the same. It changes to adapt the macro shape of the design domain. Compared to the periodic lattice structure, their research shows that the conformal lattice structure usually has a better performance for lightweight structure and compliance mechanism design (Wang, 2005). The analysis and design method for conformal lattice structure is first proposed by Wang (Wang, 2005). In his approach, the conformal lattice frame is first generated based on structure's macro shape. Then the effective stiffness matrix for a unit cell is established to describe the relationship between the nodal displacement and force. Based on this analysis method, size optimization on thickness of lattice struts can be done to achieve desired performance of a structure. Based on Wang's method, a general DFAM method for lattice structure is proposed by Rosen (Rosen, 2007). In this method, a process-structure-property-behavior model is used to analyze and design lattice structures on a mesoscale. Unlike Wang's method, struts of lattice are divided into ten groups and in each group, thicknesses of struts are equal. Although this method can dramatically

reduce the number of design parameters, the principle of dividing struts into 10 clusters is still unclear.

More recently, another conformal lattice design method is presented by Nguyen et al. (Nguyen et al., 2013). The design process of this proposed method consists of two main steps. The first step is to generate conformal hexahedral mesh for cells in a cell library, and then to populate the mesh with selected cells. After generating conformal lattice frame, in the second step, the optimization algorithm is developed to determine the diameter of each strut. Unlike traditional ground structure methods, the optimization process presented in this paper removes the rigorous large-scale multivariable topology optimization by utilizing a heuristic algorithm. This optimization only has two design variables which are the largest and smallest diameter of lattice strut. Local stress for each lattice unit cell is computed by FEA. And the diameter of each strut in lattice unit cell is determined by local stress and the range of diameter determined by two design variables. For load adaptive pseudo-periodic lattice structure, Chen (Chen, 2007) has proposed a design method based on 3D texturing mapping. In his method, a space warping technique is used to distribute materials based on stress distribution. The unit cells are stretched from low stress place to high stress place. The lattice structure designed by this method is shown in Figure 10. Another similar load-adaptive lattice structure design method is developed by Brackett et al. (Brackett et al., 2011a). Instead of using space warping technique in Chen's method, a dithering method is used to represent a gray scale stress fringe with variably spaced black dots. These spaced black dots can be also used as the lattice cell's vertices. Like Chen's approach, this design method also enables the variation of lattice size and shape according to stress distribution inside the design space. It is clear that both Chen and Brackett's design methods are computationally efficient, since they do not need any iteration for an optimization. However, there are two obvious disadvantages for these two design methods. Firstly, to evaluate the performance of generated pseudo-periodic lattice structures has a huge computational burden, since homogenization theory is no longer suitable to analyze this type of structures. Secondly, it is also skeptical to use the stress distribution of initial design domain with solid material to represent the stress distribution of the design domain filled with lattice structures. Recently, Teufelhart and Reihart (Teufelhart, 2012, Reihart and Teufelhart, 2011, Reihart and Teufelhart, 2013) proposed an adaptive lattice structure design methods based on force flux. In their method, customized lattice frame is firstly established based on the force flux in a design domain under a given load. The size optimization method is applied to optimize thickness of lattice struts. Based on this method, it is possible to achieve equal stresses in the whole structure for each struts and gain a better lightweight performance. However, to generate force flux for a design domain with complex geometrical shape and the boundary condition is still a very difficult task for both designers and software.

Figure 10 Pseudo-periodic lattice structure generated by 3d text mapping technique (Chen, 2007)

Figure 11 Pseudo-periodic lattice structure generated based on the force flux (Teufelhart, 2012)

From the above review, it is clear that most of recent DFAM methods are trying to integrate lattice frame design and struts' thickness optimization into their design process to further optimize the performance of design. Although remarkable progress has been achieved, there still existing some design difficulties especially in the design domain with complex geometry and design requirements involves multi-discipline. Thus, the multi-disciplinary design method which can deal with complex design domain is still in need.

2.3 Microscale design

On a microscale, by controlling the fabrication parameters of an AM process, a certain microstructure can be fabricated to enhance the performance of the part. For example, Functionally Graded Materials (FGMs) can be realized by gradually changing the microstructure of one or several different compositions over the design space (Muller et al., 2012), which can improve the parts' performance or add new functions. In this section, the DFAM methods are divided into two major categories. They are DFAM methods for homogeneous microstructure and DFAM methods for heterogeneous microstructure. These two categories of design methods are briefly reviewed respectively. Like those structural optimization methods, some of these design methods on a microscale have also been studied for several decades. It is almost impossible to wrap them up into several paragraphs. Thus this paper only attempts to draw an outline of these design methods, which can give a quick guide for the designers who want to find appropriate methods for a microscale design. For more details, readers are encouraged to further read those review papers referenced in the following paragraphs.

3.3.1 Design of homogenous microstructure

For the design of homogenous microstructure, the key is to design a material with certain microstructures which can achieve the desired properties. Among different types of microstructure design methods, the design methods of composite materials consisting of a periodic microstructure have drawn much research interest, since the properties of this type of material are easy to control. Designers can easily tailor different physical properties by modifying the shape of micro unit cell like the cellular structures discussed on a mesoscale. Compared to cellular structures on a mesoscale, the periodic microstructures are more suitable for those parts with a small characteristic dimension. However, it should also be noted that both the fabrication cost and difficulty may increase for periodic microstructures even by most existing AM processes.

To design a microstructure for tailored material properties, a technique commonly termed "inverse homogenization" is firstly proposed by Sigmund (Sigmund, 1994) and its general flow is shown in Figure 12. This technique has already been discussed in the previous section for the design methods of homogenous lattice structures. In this section, some applications of this technique on a microscale design will be discussed. On a microscale, existing inverse homogenization based design methods have already cover a full range of different disciplines including material stiffness(Huang et al., 2011), passion ratio(Sigmund, 1995), electronic or heat conductivity (Torquato et al., 2002), fluidic properties of permeability and diffusivity (Kang et al., 2010), thermal expansion coefficient (Sigmund and Torquato, 1997) and Phononic/Photonic Band gap (PBG) (Dobson and Cox, 1999). Instead of only focusing on a single material property,

some design methods are developed to generally consider multiple competing material properties simultaneously. Most of them focus on the optimization of stiffness/permeability (Kang et al., 2010, de Kruijf et al., 2007b) and stiffness/conductivity (Chen et al., 2010, de Kruijf et al., 2007a). In these design methods, a Pareto front can be generated to visually help designers to keep balance of different properties depending on their specific needs. Generally, these multifunction design methods for microstructure are suitable for the products with multifunctional requirements. There is a comprehensive review (Cadman et al., 2013) on the details of existing design methods of micro cell. Thus, this paper is not going to discuss the details of them.

Figure 12 General scheme and procedure of inverse homogenization technique

Besides the design methods mentioned above which only focus on a microscale design, some design methods have been proposed to update the structures on both macro and microscale. A hierarchical numerical scheme is proposed by Rodrigues et al. (Rodrigues et al., 2002) for optimizing material distribution as well as the point-wise material microstructures concurrently. In this approach, the design process uncouples the topology optimization into two related sub problems. The outer problem deal with the spatial distribution of material, which can be regarded as the design on a macroscale. The inner problem is to solve the question of optimal choice of material microstructure. Compared to those single scale design methods, Rodrigues's method can further improve the functional performance of products. However, the connection between different optimized microstructures is not considered in this design method, which makes the optimized structures are difficult to fabricate even with advanced AM processes. Liu et al. (Liu et al., 2008) has proposed a Porous Anisotropic Material with Penalization (PAMP) method to deal with macro and micro design simultaneously. In this design method, the microstructures are assumed to be uniformly distributed in the design domain. This assumption can guarantee the connection between different micro cells. Liu's method has also been successfully been applied to the multi-objective design of lightweight thermoplastic structures with maximum fundamental frequencies (Deng et al., 2013a). Another concurrent design method is proposed by Yan et al. (Yan et al., 2014). Like Liu's method, Yan's method also assumes the microstructures are uniformly distributed in the design domain. Moreover, in Yan's method, BESO based optimization is used for both macro and microscale design. Recently, another multi-scale design method is proposed by Xu et al. (Guo et al., 2015). Compared to those design methods mentioned above, this multi-scale design method can deal with unknown-but-bounded load with a robust concurrent optimization method. This optimization can consider the worst-case scenario in a confident way. To summarize these available multi-scale design methods, it is clear most of them assume the microstructures are homogenously distributed in the design domain. Even though this simple assumption can guarantee the manufacturability of designed structures, it also restricts the design freedom of using heterogeneous microstructures to further improve the functional performance.

2.3.1 Design of heterogeneous microstructure

Compared to the design methods for homogeneous microstructure, the design methods for heterogeneous microstructures are more complex. One way to design this type microstructure is to obtain its distribution directly from the 3D scan of some existing objects. For example, in tissue engineering, the scaffold with heterogeneous microstructures (Khoda and Koc, 2013, Podshivalov et al., 2013) is designed from the CT scanning data. The scaffolds designed by this method can interface better with the surrounding tissue and facilitate more efficient rehabilitation for patients.

Another way to design heterogeneous microstructures is based on those design methods for FGMs. Generally speaking, for FGMs, there are two types of design variables. The first type of design variables is the topology of FGMs' microstructure. For those FGMs fabricated by traditional manufacturing methods, there is little design freedom for designers to optimize the topology of microstructures. Thus, designers may only select some typical microstructures shown in Figure 12 to meet their design requirements. Thanks to AM technologies, parts with optimized microstructures can be realized. Thus, some research has been done to optimize the microstructures of FGMs for the certain material properties gradient. For example, a design method for two-phase (void and solid) microstructures of FGMs has been proposed by Zhou and Li (Zhou and Li, 2008b). Like design methods of microstructures for homogenous materials, the inverse homogenization technique is also used in this method to design the Periodic Base Cells (PBCs) on a microscale. The designed PBCs vary in the direction parallel to the property gradient but periodically repeat themselves in the perpendicular direction. Moreover, to preserve the connectivity between two adjacent micro cells, three different methods, namely connective constraint, pseudo load, and unified formulation with nonlinear diffusion are proposed in this design method. Another inverse homogenization techniques based design method is proposed by Radman and et al. (Radman et al., 2013a). Like Zhou and Li's (Zhou and Li, 2008b) design method, the microstructure of FGMs in Radman's design method is also composed of a series of PBCs in the direction of properties variation and self-repeated in other directions. However, instead of using SIMP for topology optimization in Zhou and Li's method, BESO is used in Radman's method to obtain the optimized microstructures of each cell. Moreover, in Radman's method the PBCs are optimized progressively by considering three base cells at each stage. This innovative technique guarantees the connections between adjacent PBCs with high computational efficiency. More recently, another inverse homogenization based microstructure is developed by Radman et al. (Radman et al., 2014). Two different functions are considered in their latest design method. In this design method, the overall stiffness of FGMs can be maximized with a prescribed variation of thermal conductivity. This design method is more useful for the design of multifunctional parts.

(a) Particulate FGMs (Rajan and Pai, 2014) (b) Columnar FGMs (Kaysser and Ilschner, 1995)

(c) Skeletal FGMs (Vel and Batra, 2002)

Figure 13 Typical types of microstructures of FGMs

The second type of design variables of FGMs includes spatial distributions of volume fractions for different material phases, orientation distribution for reinforcement fibers and other parameters of microstructure. In terms of the design parameterization scheme of the second type of design variables, existing methods can be categorized into two main types: discrete modeling and functional modeling. In the first type, different types of discrete models are used to divide the design space into sub-regions or elements whose parameters of material microstructure are assumed to be homogenous or can be interpolated from discrete control points. In most one-dimensional FGMs optimal design methods (also known as unidirectional FGMs design) where the parameters of microstructure only vary along single direction, a design domain is usually divided into a number of homogenous layers (Nadeau and Ferrari, 1999, Cho and Ha, 2002b, Na and Kim, 2010). For two-dimensional FGMs optimal design methods (also known as bidirectional FGMs design) where the parameters of microstructure of constituents vary inside a two-dimensional plane or surfaces, rectangular elements are usually used to separate the dimensional design space (Cho and Ha, 2002a). For the three-dimensional FGMs optimal design (also known as tri-variate FGMs design) where the parameters of microstructure of constituents vary inside three-dimensional space, tetrahedron elements are used by Hu et al. (Hu et al., 2008) to maximize the stiffness of 3-dimensional I beam as well as minimizing the structural weight. The advantage of discrete modeling methods is its flexibility. This type of parameterization scheme can represent an arbitrary complex distribution of design parameters inside the design domain. However, the disadvantage of the discrete model is the non-trivial computational load when the number of discrete elements is very large. This is simply due to the large number of design variables of discrete modeling methods (Kou et al., 2012).

Instead of modeling FGMs distributions of spatial discrete elements, functional modeling methods (Kou and Tan, 2007) are also available in the optimal design of FGMs. In the functional modeling methods, the distributions of parameters of microstructure can be depicted by the given analytical functions. In one-dimensional FGMs design, power-law based functions are most widely used to represent the distribution of volume fractions in some one-dimensional FGMs design methods (Na and Kim, 2008, Ootao et al., 1999). Besides power-law based functions, other types of analytical functions, such as exponential and parabolic functions (Elishakoff et al., 2005), parametric Bezier curve function (Huang et al., 2002) and generalized Taylor expansion (Biswas et al., 2004) are also used to represent the distributions of FGMs' constituents. Similar functions are also used to represent the distributions of parameters of microstructure in the two and three dimensional designs. For example, multivariate polynomial functions are used to model the heterogeneities of 2-dimensional FGMs (Nemat-Alla, 2003, Hedia et al., 2004). As to three-dimensional problems, trivariate splines functions are used to describe the heterogeneous constituents' distribution in three-dimensional space (Hua et al., 2004, Martin and Cohen, 2001). Besides using a single function to describe the material distribution, a procedural model is developed by Kou and et al. (Kou et al., 2012) to modeling material distributions with multiple functions. In Kou's method, a multiple distribution functions are modeled in a tree structure. The parameters of microstructure at any given point can be evaluated by execution of a collection of

procedures. In each procedure, a single analytical function is used to evaluate the material distribution. Compared to those functional modeling methods with a single function, this procedure modeling method can provide more flexibility for designers to express a complex distribution inside the design domain. Generally, compared to the discrete modeling method, the functional modeling can significantly reduce the number of design variables in the optimization process, since only several coefficients of a distribution function are regarded as the design variables. Despite the obvious advantage of functional modeling, it should be noted that this modeling method still has some limitations. For example, the choice of a distribution function is largely depending on the designers' experience. It is clear that different distribution functions may lead to different optimal performance. Thus, the quality of distribution functions is really important for functional modeling methods.

The objective functions of the second types of design variables of FGMs also vary dependant on the tasks and application considered, but usually include mass, thermal stresses, fracture resistance, static and dynamic responses, heat transfer and insulation. Table 3 is presented to categorize the existing optimization methods of FGMs into five different application fields. For each application field, the design methods are further divided into three sub-groups according to its design dimension. From this table, it is clear that most existing optimization methods of FGMs are related to its thermal performance. This is simply due to the outstanding performance of FGMs on heat resistant. Moreover, it can also be concluded that most optimization methods can only deal with one or two-dimensional design. One reason to explain this is that the limitation of conventional manufacturing methods. Furthermore, the heavy computational load for the optimization process is another obstacle to explore the optimal distributions of parameters of microstructure in a three-dimensional space.

Table 3 Optimization method for FGMs

Besides separately considering those two types of design variables of FGMs, some design methods of FGMs also try to integrate these two types of design variables together. For example, a two-stage method for fusion cage design is developed by Lin et al. (Lin et al., 2004). In this design method, material density distribution is firstly optimized based topology optimization methods. Then a topology optimization method is used to generate periodic microstructures for porous isotropic materials. The final design is generated by integrating design of the two-scaled structures. Another general computer-aided FGMs method is proposed by Chen and Feng (Chen and Feng, 2003, Chen and Feng, 2004). In this design method, a design process of heterogeneous material is decoupled into a sequence of steps to find the optimal macro geometrical parameters as well as the distribution of material constituents. This design methods can deal with the optimization in macro and microscale sequentially. Thus, it can be considered as a multi-scale design method. Besides this method, there are also few other multi-scale methods (Carbonari and Silva, 2010, Rubio et al., 2011) available for FGMs. In these methods, topology optimization methods are usually used to optimize the structures' macro shape and the distribution of material constituents. However, most of these existing multi-scale design methods can only deal the one-

dimensional FGMs optimization due to the heavy computational load as well as the limitation of traditional manufacturing methods.

2.4 Summarization

Admittedly, in this paper, the objective specific DFAM methods for functional performance are divided according to different design scales. However, it does not mean that there is always a strict and clear boundary to limit the design scale of DFAM methods. For example, some DFAM methods, such as inverse homogenization technique can be applied to design the unit cell on both micro and mesoscale. But, there is only a few DFAM methods considering the design with multi-scale complexity. Moreover, most multi-scale DFAM methods also assume the microstructures are uniformly distributed, which may restrict the design process to further improve parts' performance. These situations simply due to the limitation of traditional manufacturing methods. For instance, although sandwich panel has a better mechanical performance than solid panel, the high manufacturing difficulty and cost prevent the wide adoption of this type of structure for products with complex geometry on a macro level. Thus, a decision has to be made by designers between complexities in different design scales and manufacturing cost. This situation has been changed by using AM technologies. Structures with the complexity both on a meso and macroscale can be designed without increasing the manufacturing cost and difficulty. Therefore, one of possible ways to further improve the functionality of designed products is to generally consider DFAM methods on different design scales and integrate them in a multi-scale design framework.

3 General DFAM methods

Rather than only focusing on the functional performance, some general DFAM methods have been formulated recently. These general DFAM methods take into account both functionality and other product life cycle objectives, such as cost and manufacturability. In this section, some current available general DFAM methods will be reviewed respectively. A comparison between different general DFAM will be discussed at the end of section.

A formal framework based upon the process-structure-property relationships is proposed by Rosen (Rosen, 2007) and further developed by Chu and et al. (Chu et al., 2008) to design a cellular structure on a mesoscale. This general design framework is shown in Figure 14. Unlike those design methods which only consider the functionality of designed cellular structure, Manufacturable Elements (MELs) are proposed in this general design methods as an intermediate representation for supporting AM fabrication. Thus, in this general design framework, both cellular structure's function and its manufacturability are considered.

Figure 14 General DFAM method for cellular structure (Rosen, 2007)

Another general structured DFAM method is proposed by Ponche et. al. (Ponche et al., 2012). This design method consists of three main steps: global analysis, dimensional and geometrical specification design and fulfillment of manufacturing. These three steps enable the gradual

inclusion of manufacturing knowledge in the design process. Compared to those design methods which only locally modify the design parts for the improvement of manufacturability, this global DFAM method may achieve a better design result since it considers the manufacturing limitation at the beginning of the design process. Recently, another general DFAM methodology by the same author (Ponche et al., 2014). Compared to its previous version, the latest general method adds functional optimization and manufacturing paths optimization into their general design framework. Thus, it can further improve products' functional performance and manufacturability.

Those design methods mentioned above mainly focus on a single part or the product without consideration of assembly. Thus, these design methods are called as part-level design in this survey paper. However, as to additive manufacturing, the design methods for product-level are also essential. Some case studies (Becker et al., 2005, Gibson et al., 2010) have been done to show that both assembly and functional performance can be optimized by redesign of assembly relationship between parts in a product. This design process is usually referred as part consolidation. Figure 15 shows a typical consolidation process of aircraft duct. Because of the limitation of conventional manufacturing methods, 16 parts are needed to assemble for this aircraft duct. After part consolidation process, only one part is needed to be fabricated by AM processes, and the overall functional performance can also be improved. Even though a great advantage of consolidated products has been shown in these case studies, there is little theoretical research on the part consolidation design method specifically for AM process. Most design methods used in current case studies rely on traditional Design For Assembly and Manufacturing (DFAM) techniques with consideration of some unique capabilities of AM processes.

Recently, Boyard et al. (Boyard et al., 2014) managed to propose a product-level design methods based on the modification of classical DFMA methodologies. Compared to those part-level general design methods mentioned above, the most marked feature of this general DFAM methods is its ability to design the assembly relationship between parts in a complex product with consideration of both functionality and manufacturing. This unique capability of the proposed method is enabled by a modular and modifiable function graph in a conceptual design phase (shown in Figure 16). In this function graph, each function is represented by a sphere node and these nodes are linked by segments to indicate direct relationship of functions and spatial locations. Based on the relationship of functions and manufacturing capabilities of selected AM processes, functions can be divided into several sets. In each set, only one part will be designed to realize all the functions in this set. Based on the proposed function graph, DFA (Design for Assembly) and DFM (Design for Manufacturing) can work in parallel other than in sequence. Moreover, the co-design process can also be implemented in any moment of overall design process. Thus customized design can be also achieved. Generally speaking, this proposed method discussed in the reference (Boyard et al., 2014) only provides a rough framework. More detail work should be done in the future.

Figure 15 Part consolidation process of aircraft air duct(Gibson et al., 2010)

Figure 16 Function graph (Boyard et al., 2014)

Table 4 provides a comparison of the three general DFAM methods discussed above. It is manifested that each general design method has its strong points. Thus, for designers, it is important to select a suitable design method with respect to their specific design requirements. Moreover, instead of using those general design methods mentioned above alone, it is also possible to integrate DFAM methods discussed in the Section 2 which mainly focuses on functional improvement into those general DFAM methods to further improve functional performance of products as well as reducing manufacturing difficulties.

Table 4 Comparison between different general DFAM methods

4 Conclusions and Perspectives

Unique fabrication capabilities of AM processes have offered great opportunities and challenges for designers. To meet these opportunities and challenges, specific design methods are needed to consider these unique capabilities of AM processes. In this survey, based on the given DFAM concept, existing DFAM methods for functional improvement are divided into two groups and reviewed respectively. For the first group of design methods which primarily focus on the improvement of parts' functional performance, there are numerous available design methods on different design scales for different functional purposes. Among these design methods, topology optimization plays the most significant role on all design scales. A suitable design method or a combination of several methods should be carefully selected by designers according to their design objectives and selected AM processes. As for general DFAM methods, there is only little research. Most current research only focuses on part-level design. Even though there are a few successfully design cases to illustrate the advantages of part consolidation and other product-level general design which takes assembly relationship into consideration, there is still little theoretical research on this field. Thus, a general design method which can consider both assembly and functionality of designed products is still in need.

Generally speaking, comparing to objective specific DFAM methods for functional improvement, general design method can provide a broad view to consider both functional performance and other product life-cycle objectives in a systematic framework on both part and product level. Thus, general DFAM methods are more useful and practical for novice designers of AM technologies. However, it should be noted that the specific objective DFAM methods would be much powerful in terms of each specific design fields; therefore, it is necessary to integrate a suitable objective specific DFAM method into the general DFAM framework. At the end, several future research directions of DFAM are pointed out:

- 1 To synthesize design methods of different design scales. Comparing to the design methods on a single scale, multi-scale design methods may further improve the products functionality. However, there are only a few multi-scale design methods, and most of them can only deal with

homogenous structures. Thus, to further improve the functional performance of designed parts, more multi-scale design methods for heterogeneous structures are needed.

2 To develop a DFAM method enabling multifunctional and multidisciplinary design. Most current DFAM methods for functional improvement focus on optimization of a single function or multiple function in a single discipline. However, in some design cases, parts may have several functions. Thus, it is necessary to develop a DFAM method which can simultaneously consider multiple function in multiple discipline.

3 To develop a general product-level DFAM method to simultaneously consider the assembling relationship and functionality of products. Now, most existing general DFAM methods mainly focus on part-level design. For product-level design, the assembling relationship is usually optimized by traditional DFMA methods which fail to consider the unique capabilities of AM processes for the improvement of functionality. Thus, a general product-level DFAM method is urgently needed to reduce assembling difficulties or parts count as well as to increase the overall performance of products.

4 To develop a user-friendly CAD tool enabling the design of products with multi-scale complexity. Based on existing feature-based CAD software, it is difficult to build and modify the model with complex multi-scale features. This issue restricts the design innovation on hierarchical structure with high functional performance. To solve this problem, a user-friendly CAD tool is needed to help designers build model with multi-scale complexity in an easy way.

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