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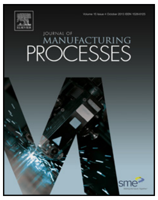

Technical Paper

A new part consolidation method to embrace the design freedom of additive manufacturing

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ABSTRACT

As additive manufacturing (AM) evolves from Rapid Prototyping (RP) to the end-of-use product manufacturing process, manufacturing constraints have been largely alleviated and design freedom for part consolidation is extremely broadened. AM enabled part consolidation method promises a more effective way to achieve part count reduction and the ease of assembly compared with traditional Design for Manufacture and Assembly (DFMA) method. However, how to achieve AM enabled part consolidation is not well developed. In this paper, a new part consolidation method comprehensively considering function integration and structure optimization is proposed. This presented method is characterized by two main modules. The first one is to achieve better functionality through surface-level function integration and sequential part-level function integration based on design specifications with an initial CAD model which is designed for conventional manufacturing process. The other module is to realize better performance through the introduction and optimization of heterogeneous lattice structures according to performance requirements. The proposed part consolidation method highlights itself from the perspective of functionality achievement and performance improvement. An example of a triple clamp is studied to verify the effectiveness of the proposed model. The optimized results show that the part count has been reduced from 19 to 7 with a less weight by 20% and demonstrates better performance.

1. Introduction

In order to stay competitive in modern production industry, products should be designed and manufactured within the following two opposite objectives: decreasing time and cost; increasing quality and flexibility. Part count reduction as one of the effective ways to reduce process time and cost has received more and more attention in the past decades. One feasible way to realize part count reduction is part consolidation which is defined as a process of composites fabrication in which multiple discrete parts are designed and fabricated together into a single part, thus reducing the number of fabricated parts and the need to join those parts together [10]. A reduction in the number of assembly operations can have a tremendous impact on production costs and difficulties of products. Firstly, there is no need for dedicated tooling, for example, fixture, and fasteners and potential assembly difficulties like joining method is avoided. Furthermore, it is often possible to design the consolidated parts to perform better than the assemblies. Ultimately, a reduction in part count means that product complexity is reduced from management and production perspectives since fewer parts need to be tracked, sourced, inspected. Part consolidation is intensively studied in conventional Design Theory and Methodology (DTM) such as Design for Assembly (DFA) [1], Design for Disassembly (DFD) [8], and Design for Manufacture and Assembly (DFMA) [6]. The problem is that design freedom of part consolidation is heavily stifled by the requirements of Design for Manufacturing (DFM), which leads to the limited reconstruction by only deleting fasteners and merging existing parts together. Moreover, part consolidation stagnates without taking into consideration of structural optimization of the merged design space to achieve better performance; therefore, a global optimal consolidated structure is not achieved. As AM process evolves from RP to the end-of-use product manufacturing method, manufacturing constraints are largely alleviated and the design freedom is extremely expanded. For example, design limitations by conventional manufacturability such as uniform wall thickness, avoiding sharp corners, and minimizing weld lines in injection moulding can be overcome by AM [12].

AM is defined by the American Society for Testing Materials (ASTM) as "a process of joining materials to make object from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [3]. From manufacturability

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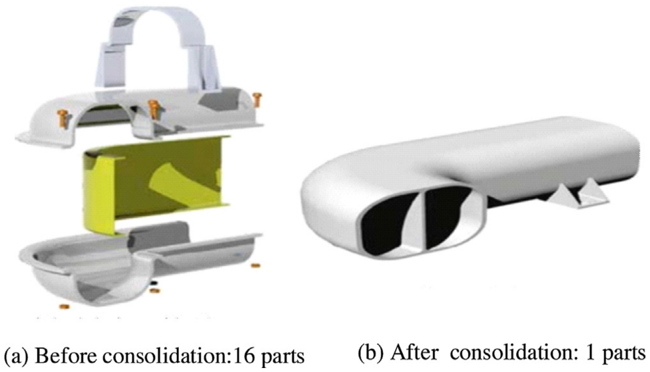
(a) Before consolidation:16 parts (b) After consolidation: 1 parts

Fig. 1. Aircraft duct examples [11].

perspective, the benefit by taking AM process (also well known as rapid manufacturing (RM) at the beginning) is the ability to virtually manufacture parts of any geometric complexity without tooling, which used to be one of the typical restrictive factors of today's product development [14]. From design perspective, the advantage of AM over conventional subtractive or formative methods is well illustrated by the great design freedom. These design freedoms enabled by AM capabilities are reflected in four categories: shape complexity, hierarchical complexity, material complexity and functional complexity [11]. Therefore, the design freedom for part consolidation and performance improvement is largely expanded. In Section 2, a literature review of AM enabled design methods for part consolidation and design methods for performance improvement is given.

2. Literature review

There are numerous literatures on adapting AM to do part consolidation [4,11,14,16,17]. The first and well known reported part consolidation case using AM capabilities was the aircraft duct redesign case [11] shown in Fig. 1. Since the limitation of conventional manufacturing processes, 16 parts are needed to be assembled to accomplish this aircraft duct. After part consolidation process, only one part is needed to be fabricated by AM process. Realizing the opportunities brought by RM, Becker et al. [4] introduced some major design guidelines for rapid manufacturing and applied these guidelines to a case study of a mix device. The optimized part has advantages in reduced part count, less assembly effort and advanced functionality. A similar case is a fluid control valve with 18 components, which is redesigned to be a new one consisting of 8 parts with better performance based on DFMA and RP [17]. An important application in automobile was reported by Hopkinson et al. [14] to redesign a door assembly that is composed of 11 pieces for an automotive application subjected to environmental burden and financial profits/costs for end-of-life recycling. It is important to note that although all these reported cases produced new and better design to achieve part consolidation, there is no clear design framework to implement the design process and the extent of success depends much on designers' experience and understanding of the functional requirements.

To overcome the drawback of difficulty in determining the real optimized characteristics for a given AM process from an initial CAD model that is designed for traditional fabrication processes, a global approach (shown in Fig. 2) aiming at defining part shapes from the manufacturing process and the functional requirements is presented by Ponche et al. [16]. This design method is composed of three steps. The first step is a global analysis which allows the delimitation of the design problem in terms of geometrical dimensions in relation to the dimensional characteristics of the AM process. The second step allows the fulfilment of the dimensional and geometrical specifications in relation to the AM process capability and the finishing process characteristics. Finally, the third step allows the fulfilment of the physical and assembly requirements in relation to the capability of the AM process. The proposed design method is applied to a case of a robot hinge made in stainless steel. Based on the building orientation and mechanical behaviour analysis, the final geometry is given (see in Fig. 3). However, functional surfaces and functional volumes are not well defined and the gap between these two functional units is not bridged.

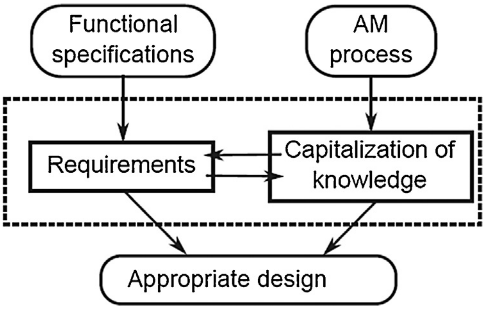

Fig. 2. A global design approach [16].

Moreover, in the reported related research, structure optimization corresponding to load conditions and other performance requirements are rarely discussed. Actually, the design space derived from part consolidation process can be further partitioned and optimized to achieve better performance. To improve products' performance, lattice structure on a meso-level (0.1–10 mm) is widely used [7,13,22]. This structure is defined as a meso-level structure which consists of an interconnected network of solid struts or plates. By carefully designing the topology of a network of lattice and its struts' thickness, some desired structural properties, such as high stiffness weight ratio and high energy absorption rate, can be achieved. Thus, the lattice structure is usually used to replace the solid material for the further performance improvement.

Design methods for lattice structure can be mainly divided into two types. They are design methods for homogenous lattice and design methods for heterogeneous lattice. For homogenous lattice structure, since the homogenous lattice structure on a meso-level can be regarded as homogenous material, traditional material section method can be used to select an appropriate type of homogenous lattice structure [2]. Compared to design methods for homogenous lattice structure, design methods for heterogeneous lattice are more complex because the struts' thickness, size and orientation of lattice unit cell were unevenly distributed in the design domain. To optimize the struts thickness distribution, some structural optimization methods [18–20] are used. Besides optimizing its struts' thickness distribution, the shape and orientation of lattice unit cell can also be optimized to achieve a better performance [7,19,23]. Generally, the heterogeneous lattice structure can always achieve a better performance than its homogenous counterpart [21]. As shown in Fig. 4, under the same load condition, compared with homogenous lattice beam in (a), the heterogeneous lattice structure in (c) shows a less maximum displacement since density distribution is in proportion to load condition [21].

In order to realize better functionality and better performance with respect to functional requirements and manufacturing constraints, a new part consolidation method which synthesizes function integration and structure optimization is proposed. AM enabled part consolidation is realized from a functional standpoint allowing better functional achievement and performance; meanwhile, it increases the scope in the search for better design solutions.