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ScienceDirect

Procedia CIRP 50 (2016) 414 – 419

www.elsevier.com/locate/procedia

26th CIRP Design Conference

Build Orientation Determination for Multi-material Deposition Additive Manufacturing with Continuous Fibers

Yicha Zhang[a], Wout De Backer[b], Ramy Harik[b]*, Alain Bernard[a]

[a]*IRCCyN, Ecole Centrale de Nantes, UMR CNRS 6597, 1 rue de la Noë, Nantes 44300, France*
[b]*McNAIR Center, University of South Carolina, 1000 Catawba Street, Columbia, SC 29201 USA*

* Corresponding author. Tel.: +1-803-636-5370; *E-mail address:* harik@cec.sc.edu

Abstract

Build orientation of a part in Additive Manufacturing (AM) has complex effect on part's quality, process planning, post-processing, processing time and cost, etc. The identification of the optimal build orientation for a part is one of the main contents of process planning in AM. In this paper, a build orientation optimization strategy is developed for a new AM process, multi-material deposition with continuous fibers, to improve the part quality while reducing the production time & cost. First, a set of finite alternative build orientations are generated by using surface shape feature with associated rules derived from the specific characteristics and constraints of the new developing AM process; then, a multi-attribute decision making algorithm is applied to determine the optimal orientation according to preset preferences. A case study is presented for demonstration.

Peer-review under responsibility of the organizing committee of the 26th CIRP Design Conference

Keywords: Build Orientation Optimization; Process Planning; Contenuous Fiber; Composite Additive Manufacturing

1. Introduction

Additive Manufacturing (AM) has been developed rapidly in recent years. The application scope and material range are expanding day after day. New AM process and AM integrated process are proposed and implemented by research communities and industries to deal with current challenges and arising new needs in the manufacturing domain [1-7]. Using the AM processing scheme, layer-by-layer material deposition, to fabricate composite parts so as to meet some special requirements in aeronautics application domain, where reinforced and lightweight structures are usually demanded, is a new development direction. A couple of researchers had developed composite materials and related AM processes to fabricate reinforced parts [8-11]. There are two main groups of methods for composite AM, one is direct composite AM which can build composite parts directly and the other is indirect composite AM that is used by providing soluble core materials to facilitate the fabrication of complex composite parts for traditional processing technologies [11]. In this paper, the scope is direct composite AM via fused deposition modeling (FDM). The major drawback of producing composite parts via FDM is the need to produce a reinforced polymer filament compatible with existing FDM equipment, which is not a trivial task [11]. Most of the current research practice in this direction is to develop new materials with short fibers mixed for reinforcement. However, the fabricated composite parts have different properties to traditional composite parts and the fibers are not continuous. In addition, those developed new materials are usually not compatible with current FDM machines. To solve these problems, a new direct composite AM process, multi-material deposition reinforced with continuous carbon fiber, is proposed and under development. In the first development stage, a 3-axis FDM experimental platform, which will be introduced later in this paper, had been constructed to build 3D parts with fully continuous carbon fibers for reinforcement. For 3-axis AM processes, also called flat-layer concept AM processes, there are mainly two directions to optimize the build procedure for a given part, one is optimizing layer filling pattern (tool-path planning) and the other is optimizing the build direction (orientation optimization). To optimize the part quality when

Peer-review under responsibility of the organizing committee of the 26th CIRP Design Conference
doi:10.1016/j.procir.2016.04.119

using this process, there is a need of an orientation optimization method. However, due to the special processing characteristics of this new FDM process, current orientation optimization methods in literature can't be directly adopted. Hence, this paper is dedicated to propose an orientation optimization method for the new FDM process.

The structure of this paper is organized as follows: the second section will review current orientation optimization methods in literature; the third section will introduce the newly developed FDM platform with its specific processing characteristics and constraints; the fourth section will present the proposed customized orientation optimization method; the fifth section will present a demonstration and the last section will conclude the research with some perspectives.

2. Orientation optimization methods in literature

Build orientation, as one of the preparation or process planning steps in AM, is very important to the production result since it affects the downstream preparation procedures, such as support generation, slicing, tool-path generation, etc., which co-determine the final build time, cost and quality. Due to the importance, many researchers have investigated this problem for a long time. To solve this problem, there are two main tasks [12], one is identifying a set of alternative orientations from an infinite alternative build orientation space for a 3D part since it can rotate freely around three axes with infinite angle options in the 3D build space, and the other is to apply multi-criteria decision making method for determining the optimal out of the pre-identified alternatives. To solve the first task, there main two groups of methods, rule or knowledge based method and sampling method or listing method. For the rule or knowledge based method, base planes, key surface features or user-defined surface features on a 3D part model are used with associated rules to suggest a set of finite alternative build orientations [13-18]. For the sampling or listing method, a mathematical or statistical method was used to explore a predefined smaller orientation space from the theoretically infinite solution space [19-22]. Genetic algorithm and RSM (response surface methodology) are the two representatives. To deal with the second task, multi-criteria were usually defined to be considered in order or simultaneously through the applying of suitable decision algorithms. Since the build orientation affects many downstream processing chains, usually a group of factors with complex interrelations should be considered. When adopting a sampling or listing method with mathematical or genetic algorithms to do the optimization, the computation is very costly as the searching step length decreases. When considering multiple factors or criteria simultaneously, the computation becomes more complex due to the additional computation for multi-objective functions. Hence, this kind method is not efficient to solve the first task [22]. While rule or knowledge based method is more effective to identify a set of finite alternative orientations since it can focus on more practical alternative orientations and implicitly capture the embedded design intention when a part is designed for the process. Hence, to save computation time and to simplify the orientation problem of the new composite AM, this paper uses a feature and rule-based method to generate finite alternative orientation set and a multi-attribute decision making model is applied. However, due to the special processing characteristics and constraints of the new composite AM, the former method cannot directly be adopted but needs to be adapted. To conduct effective optimization for any engineering problem, the specific characteristics and constraints of the particular technology under investigation should be firstly considered [23]. Therefore, there is a need to deeply analyze the new FDM process so as to develop a customized orientation optimization method.

3. Processing characteristics of the new composite AM

As a platform to experimentally prove the developed new composite AM, an industrial 6 degree of freedom KUKA KR6 R700 robot is modified and supplied with a heated bed end effector as shown in Fig. 1. Currently, the build bed can translate through 3 axes to make this platform function as a 3-axis 3D printer. Multiple nozzles are mounted to an overhang frame to extrude multiple materials, including support material and part materials, bonding plastic and carbon fibers.

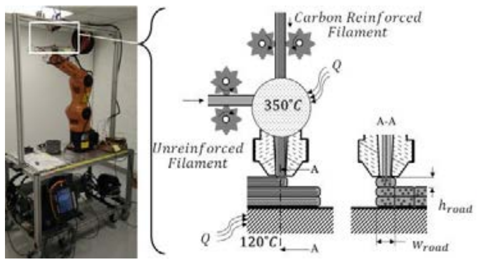

Fig. 1. The new composite AM experimental setup and mechanism

A special 3D printer nozzle designed and dedicated to print continuously reinforced carbon fiber filament is used. This setup allows reinforcement with carbon fibers not only in plane, but also out of plane since continuous fibers can jump from one layer onto the next adjacent layer without cutting if the tool-path is well-planned. In-plane reinforcements with carbon fiber, a concept similarly proven by the team of the Markforged Mark one printer [24], have proven to result in a specific flexural modulus higher than 6061T6 Aluminum. The interlaminar strength can be increased by printing in the build direction, and additionally boosts up this interlaminar strength through the addition of carbon fibers. The current capabilities of the system have only been proven in a standard XYZ configuration, which allows for standard layer-by-layer specimen to be printed. An example of a continuous carbon fiber reinforced 3D printed specimen is shown in Fig. 2. To print continuous carbon fiber reinforced of parts, a very similar approach is used to the standard FDM printing process except the extrusion of fibers with fused bonding plastics. Uniform slicing is used to adapt for the current 3-axis FDM composite AM experimental platform.