Journal of Manufacturing Processes 33 (2018) 150–160

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

A novel 6-axis hybrid additive-subtractive manufacturing process: Design and case studies

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ARTICLE INFO

Keywords:
Hybrid additive-subtractive manufacturing
Multi-axis additive manufacturing
Surface quality
Additive manufacturing
Staircase error

ABSTRACT

Additive manufacturing has been employed in numerous areas owing to its advantages of fabricating complex geometries and creating less material waste. Nevertheless, parts manufactured by additive manufacturing processes tend to have poor surface quality and low dimensional accuracy. To overcome the limitations of additive manufacturing technologies, the favorable capabilities of subtractive manufacturing, i.e., high surface quality, can be integrated to form a hybrid process. A novel 6-axis hybrid additive-subtractive manufacturing process is proposed and developed in this paper. The hybrid process is realized using a six degrees of freedom (DOF) robot arm, equipped with multiple changeable heads and an integrated manufacturing platform. Based on the obtained results from different case studies, the hybrid additive-subtractive process has shown to have potentials in reducing production time, fabricating parts with better surface quality by removing the staircase error, manufacturing high quality freeform surfaces through the dynamic adjustment of tool axis direction, and eliminating the need for support structure because of the 6-DOF flexibility.

1. Introduction

Additive manufacturing (AM), also referred to as 3D printing, is defined as the "process of joining materials to make objects from 3D model data usually layer upon layer, as opposed to traditional manufacturing technologies such as subtractive manufacturing" [1]. Such unique manufacturing method creates great potential to fabricate parts with complex geometries, while causing less material waste and reducing the time to market [2]. Different types of AM technologies have been developed which can be categorized based on different factors including their raw material and building approach [3]. Due to the distinct advantages of AM compared to traditional subtractive manufacturing (SM) processes, AM technology has obtained extensive interest and is expected to revolutionize the manufacturing industry as it is nowadays [4]. However, limitations exist which are hindering the full realization of AM in different industries. For example, additive manufactured parts usually have lower accuracy [5] and strength, unsatisfactory surface quality [6], and longer manufacturing time [7]. Therefore, it is necessary to improve the dimensional and mechanical performance of AM processes while reducing the production time [8].

One of the approaches to resolve the current restrictions of AM processes and further improve the part quality is the development and application of multi-axis 3D printing mechanisms [9]. Compared with traditional/commercial AM processes and machines with three degrees of freedom (DOF), multi-axis AM processes can provide higher degrees of mobility (e.g., four, five, or six) depending on the machine kinematics and configuration of the manufacturing platform. The additional degrees of mobility can reduce the production time as less setup changes are required. Furthermore, it can improve the quality of parts due to less re-location and re-positioning of parts and thus, eliminating the risk of stacked tolerances. To achieve multi-axis 3D printing, three popular methods are usually adopted: (i) integration of a 3-DOF AM process/machine with a rotatory printing platform which introduces one, two or higher additional degrees of mobility to the current mechanism [10], (ii) employing an industrial robot arm with more than three DOF which can also be integrated with a rotatory build platform to further minimize the mobility constraints [11], and (iii) developing a kinematic mechanism with more than three DOF instead of using commercial robotic mechanisms or existing 3D printing machines [9]. Each of the reported methods has unique advantages, challenges as well as drawbacks, and requires different control methodologies and software to be developed for slicing, process planning and execution. For example, integrating a rotatory printing platform to a commercial 3-DOF machine is usually easier and can allow for printing overhangs without the need of support structure due to the additional degrees of mobility. Developing a multi-axis printing mechanism, is however, more challenging as it requires applying reverse kinematics to program the kinematic configurations of the mechanism. Therefore, employing

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https://doi.org/10.1016/j.jmapro.2018.05.008
Received 8 September 2017; Received in revised form 9 March 2018; Accepted 9 May 2018
1526-6125/

an industrial robot can simplify the development process by eliminating the need for programming the link and joint motions.

Many researchers have focused on developing multi-axis AM systems. Lee and Jee [12] proposed a 5-axis AM system by integrating a conventional 3-axis printer and an additional 2-axis based printing platform. Furthermore, an auto-partitioning slicing algorithm to build overhang/undercut features was developed. Ishak et al. [11] developed a robotic arm AM platform for plastic components and successfully applied it for multi-plane printing. A low cost parallel kinematic machine for multi-directional printing was proposed by Song et al. [9], in which the process showed potential for improving the quality of different test geometries. Rieger et al. [13] adopted a 6-axis robot for multi-axis fused layer manufacturing and analyzed the feasibility of the robotic AM station by varying the orientation of the extrusion axis. The robotic AM station was shown to have the potential for eliminating the need for support structure in overhangs, however, other aspects (e.g., surface quality) were not explored. A robot controlled AM system, which consists of a 6-axis robot arm coupled with a 2-axis tilt and rotatory system, was developed by Ding et al. [14]. A new slicing method was established to consider the overhang structures in revolved parts and was successfully implemented to build a propeller. Nevertheless, the surface quality of the printed part was not examined or compared with other processes.

Despite the advantages of multi-axis AM processes and their capabilities toward eliminating the need for support structure in overhang features, improving the quality and reducing the production time, the final quality of parts produced by AM still requires further enhancements to reach the standards of those generated by traditional subtractive processes (e.g., milling or turning processes). One of the possible approaches toward improving the AM performance characteristics (e.g., in terms of the obtained dimensional or mechanical quality characteristics) is by integrating the AM process with SM process to form a hybrid manufacturing (or multi-tasking) process. In addition to the reduced production time due to less setup changes, and higher accuracy due to less re-location of parts, a hybrid manufacturing approach allows for combining the advantages of multiple processes while minimizing their limitations and drawbacks. Hybrid manufacturing can be generally considered as the combination of any two or more manufacturing processes [15] with the aim of improving the performance characteristics. In a hybrid process, it is generally not necessary for the processes to work simultaneously; however, it should be possible to change from one process to another in the same machine/station. Traditionally, numerous hybrid subtractive or transformative manufacturing processes have been developed and reported in the literature (e.g., turn-mill, mill-grind, laser cutting and electric discharge machining (EDM), laser heat treatment and sheet metal forming, etc.) [15].

A number of researchers have also focused on developing hybrid additive processes by integrating multiple AM processes [16] or using multiple additive heads for multi-material deposition [17]. Recently, development of hybrid additive-subtractive manufacturing processes has become a promising solution for improving the current limitations of AM processes [18,19] and also an effective approach for remanufacturing applications [20]. Many research efforts have been dedicated to proposing suitable hardware and kinematic configurations, control systems, and process planning approaches for hybrid manufacturing systems [15,21,22]. The most popular hybrid design in the literature is based on the integration of conventional AM processes and SM processes, such as milling, on a single station. This can be applied by either attaching a SM head to an AM machine/mechanism or vice versa. For instance, Jeng and Lin [23] presented a new method of fabricating and modifying metal rapid prototypes and molds, where selective laser cladding process was used to build up the material layer-by-layer, and milling process was performed to machine the top surface for better accuracy and surface finish. In order to manufacture super alloy integral impellers in aero engines which are vital functional parts with complex freeform surfaces, Xiong et al. [24] adopted a hybrid process which consists of plasma deposition process and milling process and managed to improve the insufficient dimensional precision and surface quality. Karunakaran et al. [25] integrated a 3D arc weld deposition process with a commercial CNC machine, and found that the hybrid process can save time and cost of production compared to when the parts are fabricated solely by the CNC machine. Choi et al. [26] developed a direct metal fabrication technique which combines CO_2 laser welding and milling processes.

The developed hybrid processes in the literature indicate promising potential for quality improvement. Nevertheless, they lack fabrication flexibility because of having only three DOF for mobility. To address this limitation, Liou et al. [10] developed a hybrid process for metallic structures including a laser deposition system and CNC milling mechanism in one workstation with five-axis motion modes. It was shown that the five-axis hybrid process could significantly reduce the material consumption and production time. In addition, a satisfactory surface quality could be obtained by using the CNC milling process. Lee et al. [27] developed a low-cost hybrid system with an FDM (Fused Deposition Modeling) extruder and a spindle placed on each end of a rotary axis in a five-axis machine tool. A novel tool changing mechanism was also proposed for switching between FDM extruder and spindle using a 180-degree rotation of the head. A remanufacturing station including three processes of laser cladding, machining and in-process scanning was developed in [28]. The integrated station was successfully applied to remanufacture turbine blades with lower capital investment costs.

Although the discussed hybrid additive-subtractive processes can have multi-axis motions (mainly caused by the rotatory build platform), the movements of SM and AM heads are usually constrained to three axes of motions (namely X, Y and Z). Therefore, to incorporate more DOF to the SM and AM heads, employing a robotic arm or mechanism with more than 3-DOF is necessary. According to the literature, the only study on developing multi-axis robotic hybrid additive-subtractive process is performed by Keating and Oxman [29], where a multi-axis robotic platform named compound fabrication is proposed, which integrates additive, subtractive, and formative processes. This compound fabrication platform is applied for plastic deposition and can achieve a fast printing speed (0.2 m/s) as well as fine surface resolution for large-scale printing. In addition to the advantages obtained by employing a hybrid approach (e.g., reducing material waste, increasing accuracy, and reducing build time), adopting robotic arms for developing hybrid processes can increase the workspace adaptability and flexibility, and thus provides new manufacturing opportunities (e.g., printing on complex 3D surfaces rather than a planar surface or accessing inner surfaces or features). However, despite these numerous advantages compared to the conventional hybrid machines with motion constraints on X, Y and Z axes, development and application of robotic structures for hybrid additive-subtractive processes is still limited and not fully addressed in the literature. In addition, most of the research efforts regarding the development of hybrid processes do not consider or focus on the development of integrated manufacturing platform to support the functionality of different processes. Furthermore, in majority of the studies on hybrid additive-subtractive processes and systems, the SM process is mainly demonstrated as a surface finishing process and not as an independent subtractive process. As a result, the capabilities of the SM in hybrid additive-subtractive processes are not fully realized. An independent subtractive process in the context of this work mainly refers to a subtractive process that is not solely for the purpose of post-processing or surface finishing of previously printed additive features and directly contributes to the final geometry of the product.

To fill this research gap, a novel hybrid additive-subtractive manufacturing (HASM) process is proposed and developed in this paper. The HASM process is built based on a 6-DOF industrial robotic arm and equipped with changeable heads (AM and SM heads). In addition, an integrated hybrid manufacturing platform is designed, which consists of heated bed for AM process and fixturing clamps for SM process. In