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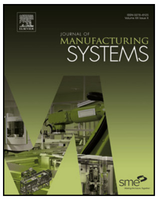

Technical Paper

Process planning for combined additive and subtractive manufacturing technologies in a remanufacturing context

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ABSTRACT

In recent years, additive manufacturing (AM) techniques provide the capability to build parts directly from CAD models by adding materials layer by layer. This technique allows producing complex parts that are not able to be manufactured by machining. However, AM techniques also present some limitations, such as poor surface quality, reduced dimensional accuracy, limited materials available and long production time when compared to CNC machining. To overcome these limitations, the combination of additive and subtractive (i.e. CNC machining) technologies is today considered as a promising solution for current manufacturing issues. This paper demonstrates the feasibility of combining these technologies for the manufacture of given parts from end-of-life (EoL) parts (or existing parts). The proposed approach aims to reuse existing parts directly to produce new parts (or final parts), avoiding the material recycling stage. The final parts are then intended for another product, namely the existing parts have a new life in their life cycle. This paper particularly focuses on the design of process planning for combined additive and subtractive processes, using the concept of AM and machining features. The design of process planning is performed based on the knowledge of additive and subtractive processes, the technological requirements, and the available resources. To respect constraints and considerations in manufacturing processes, different rules are defined and applied in the design of process planning. Finally, the efficacy of the proposed approach is demonstrated through the case study.

1. Introduction

In the past three decades, additive manufacturing (AM) has attracted an increasing attention of researchers both in the academic and industrial sectors [1]. AM is defined as “the process of joining materials to make objects from three-dimensional model data, usually layer upon layer” [2]. This offers a special ability to build complex parts, including internal structures, without using cutting tools, cooling fluid and fixture systems. Compared with conventional manufacturing processes, such as machining, AM technique presents at least three main advantages [3]. Firstly, the design freeform offered by AM enables parts with complex geometry (including internal features) to be produced, and opens new prospects for topological optimization in design of innovative products and lightweight components. AM technique has the potential for reducing energy and resource consumptions during the production process. Moreover, the design freedom of AM allows the redesign of products, meaning several products made of an assembled mechanism can be replaced by an integrated part. This results in reducing production costs and quality problems resulting from assembling operations [4,5]. Secondly, AM can reduce the supply chain of production and enhance the profit space for manufacturers. Thus, the adoption of AM offers shorter and simpler supply chains, as well as more localized production [6]. Lastly, AM technologies also provide a huge potential to reduce environmental impacts by reducing CO_2 emissions and scrap generated during the manufacturing process [3,7,8]. However, AM techniques also present a number of limitations, such as limited materials available, long production time, and poor dimensional accuracy and reduced surface quality [9]. On the other hand, CNC machining technology (a typical subtractive manufacturing process) is usually used for achieving components with high levels of surface finish and dimensional accuracy. This technology also enables a relatively short production time. Nevertheless, due to limited tool accessibility it is still relatively difficult or impossible to achieve complex geometries, such as internal structures [10]. In addition, CNC machining requires a significant human intervention for toolpath planning, especially in machining complex parts [11]. As a result, the combination of additive and subtractive manufacturing technologies is today becoming

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as a technical promising solution to minimize the limitations of individual technologies [12]. Due to the consolidated advantages of combining these techniques, this solution makes it easy to produce parts including internal features with desirable accuracy.

In the current work, a direct manufacturing approach based on combining additive and subtractive (i.e. CNC machining) technologies is proposed. Thanks to the consolidated advantages and performances of individual techniques, the proposed approach enables achieving high accuracy parts directly from end-of-life (EoL) parts (or existing parts), avoiding the material recycling phase. The obtained parts are then intended for another product, namely the EoL parts will have a new life in their life cycle. The proposed approach seems able to reduce energy and resource consumptions, as well as waste during the manufacturing process. This is today considered as an essential issue for a sustainable production system.

The article is organized as follows. A review of related works is outlined in Section 2. This provides an overview on the use of AM in different recovery strategies of EoL products, as well as the feasibility of AM techniques for remanufacturing applications. Previous works concerning the process planning for combined additive and subtractive manufacturing technologies are also reviewed. Thereafter, the proposed approach is introduced in Section 3. Section 4 presents the concept of machining and additive manufacturing features, which is used for the process planning design. Section 5 is the core of the paper, which particularly focuses on the design of process planning for combined additive and subtractive manufacturing processes. Different steps of the process planning design are deeply described. The manufacturing rules are also defined and applied to respect manufacturing constraints in the process planning design. In Section 6, the efficacy of the proposed approach is demonstrated using the case study. Finally, Section 7 presents conclusions and future work.

2. Literature review

2.1. Current research using AM techniques in repairing and remanufacturing context

A number of studies have investigated the possibility of AM techniques for repairing and remanufacturing applications. Cottam et al. [13] used laser cladding to build Ti-6Al-4V entities on Ti-6Al-4V substrate. In their work, the investigation on microstructures and microhardness of produced samples was conducted. By changing laser parameters (e.g. laser power, feed rate and traversing speed), the authors could determine what parameters can be used to repair Ti-6Al-4V components. Dutta and Froes [14] stated that directed energy deposition (DED) technologies, such as direct material deposition (DMD), are especially suited for repairing and remanufacturing, as well as adding new functionalities on existing parts. Due to the flexible material deposition configuration of a 5-axis CNC machine, these techniques have successfully been applied in remanufacturing of worn-out or damaged components (particularly for high-value components, such as turbine blades, molds and dies) [15]. Wilson et al. [16] demonstrated the efficacy of DMD technology in remanufacturing turbine blades. Rickli et al. [17] used DMD technique in an additive remanufacturing system. This system was able to restore high-value EoL cores to original specifications and qualities.

In comparison with DED, powder bed fusion (PBF) techniques, such as election beam melting (EBM) and selective laser melting (SLM), have some limitations for repairing and remanufacturing components. This is due to their limited build envelope, and the deposition of materials is only conducted on horizontal flat surfaces. However, there are numerous components, which can be repaired/remanufactured by these processes. For instance, Navrotsky et al. [18] used SLM process to repair gas turbine burner tips. This research also demonstrates the potential of SLM technique for building new features on existing components. Recently, Portolés et al. [19] proposed a qualification procedure (QP) for EBM to reproduce and repair aerospace parts. In their work, the material interface analysis, which aims to characterize mechanical properties at the interface between the base and added materials, was mentioned as one of important studies for the QP. However, no results of this study were presented. In the work of Terrazas et al. [20], the authors have successfully built a copper entity on the top of existing titanium part using EBM technology. By studying microstructures and hardness of built samples, they observed that there exists a good metallurgical bonding at the interface between Ti-6Al-4V part and built copper entity. Hinojos et al. [21] also investigated the feasibility of EBM for manufacture of multi-material parts by joining Inconel 718 with 316L Stainless Steel. These works, [20] and [21], showed that EBM not only has the potential to produce multi-material parts, but also to be used for remanufacturing applications. Nevertheless, in these works, the authors only focused on investigating microstructures and microhardness of built samples to observe phase transformation traversing the heat affected zone. To validate the strong mechanical bonding between EBM-built features and the substrate, it needs to realize the tests on mechanical properties, such as the tensile test. Mandil et al. [22] carried out a study to confirm the feasibility of EBM technique for building new features on existing parts. The existence of strong bonding between EBM-built entities and the existing part is demonstrated by the microstructure observation and the tensile test. In the similar way, Liu et al. [23] and Sing et al. [24] also investigated on microstructures, tensile and bending properties of multi-material parts built by SLM. The authors have found a good bonding at the interface between two materials. Their results have also confirmed the feasibility of SLM technique for building new features on existing components. From these survey works, the metal-based AM technologies (e.g. DMD, SLM and EBM) make it possible to obtain new parts by adding new entities to existing components. The parts obtained have a good "material health", which means that their mechanical characteristics are compatible with industrial applications.

2.2. Process planning for combined additive and subtractive manufacturing processes

Many studies have focused the process planning for machining process [25–28] and AM process [29,30]. However, limited research has focused on the process planning for combining additive and subtractive technologies. Ren et al. [31] presented a hybrid system combining laser cladding with CNC machining for repairing of dies. The authors identified four major steps for the process planning: (i) defining the damaged features, (ii) machining damaged features, (iii) depositing material to rebuild the feature, and (iv) finishing machining the feature. Kerbrat et al. [32] used a design for manufacturing approach to evaluate the complexity of features in the design stage, and identify if they can be produced either by machining or AM processes. This identification could provide a valuable insight for designing process planning for combined additive and subtractive processes. Manogharan et al. [33,34] presented a process planning framework, which combines electron beam melting (EBM) or direct metal laser sintering (DMLS) with CNC machining to manufacture mechanical parts. However, the manufacture of parts was performed in two separate phases, namely a near-net shape of parts was built by AM processes (i.e. EBM or DMLS) and the part accuracy was achieved by CNC machining. Zhu et al. [10,35] proposed the iAtractive framework, which is able to manufacture high accuracy plastic parts including internal structures,