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Partial Additive Manufacturing: Experiments and Prospects with regard to Large Series Production

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Abstract

Additive manufacturing meets the demand for highly customized and flexible production. However, the physical limitation of the material application rate causes that large volume production of such workpieces is not attractive yet. In order to push additive manufacturing towards large volume production, the impact of this limitation has to be minimized while the advantages have to be maintained. For this purpose, it is proposed in this article to combine partial additive manufacturing with other production technologies. In such a production concept, standardized base workpieces are made in large volume production first and then finalized by additive manufacturing. The finalization step adds the variant specific key features to the workpiece. This proposal is detailed by discussing the suitability of specific workpieces and outlines of the processing route. An experimental feasibility study of this principle is reported, where Fused Deposition Modeling is used to add geometric features to a base workpiece. This case study includes the development of a robot-based setup for the deposition of material with 6 degrees of freedom. This case study is used to illustrate and discuss the fundamental aspects of the conjunction of additive manufacturing with other production processes.

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1. Introduction

This article is concerned with the conjunction of additive manufacturing with other manufacturing processes. The motivation for this research arises from the fact that, despite the large interest in academia and industry, additive manufacturing techniques have not yet reached medium to high volume production [1]. The deployment in such scenarios is inhibited by the insufficient productivity of additive manufacturing processes, which is limited physically by the material deposition process. This insight triggers the research into partial additive manufacturing, meaning that only a portion of a specific workpiece is generated by additive manufacturing while the remainder is created by other processes.

In this article, such partial additive manufacturing concepts are analysed and aggregated to a more general proposal. This proposal combines subtractive, additive and joining processes, such that a contribution towards a fundamental understanding of manufacturing concepts with partial additive manufacturing is made. For this purpose, an abstract concept for a manufacturing chain and a relevant workpiece design are elaborated. The concept is named *Incremental Manufacturing*, which refers to the core idea to manufacture workpieces in small increments.

The deposition of material on a pre-shaped workpiece is a crucial piece of technology towards the combination of Additive Manufacturing with other processes. This aspect is elaborated in a case study which considers a robot-guided fused deposition modeling head to add geometric features on a non-plain surface. This experiment setup is used to investigate path planning algorithms and practical issues involved with *Incremental Manufacturing*.

The article is organized as follows. In Section 2, partial additive manufacturing and hybrid manufacturing machines, which integrate multiple manufacturing processes are reviewed. Section 3 contains the proposal for *Incremental Manufacturing* and outlines an example product to be produced by such a system. Section 4 reports a case study, where additive finalization is implemented into a robot cell. Experiments are conducted, discussed, and lessons learned are stated. Section 5 concludes this article.

2. Related Work

In order to lay out the foundation for this article's contribution, this section provides an overview of technologies and machines of relevance for partial additive manufacturing. Be-

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sides additive manufacturing, this covers machines with multiple processes, so-called hybrid manufacturing machines.

The economic perspective of additive mass manufacturing is approached by Berman [2]. A number of existing business cases are analysed, such as on-demand manufacturing for spare parts or custom parts. Other business cases rely on the fact that, by employment of additive manufacturing, production and design planning can be separated. If such business models could be extended by new flexible production technologies, further growth is to be expected. Thus, the conjunction of additive manufacturing with other production technologies, which is an objective of this article, will be a driver for new business models.

The technological perspective of additive manufacturing processes is reviewed extensively by Gao et al. [1]. This resource attenuates the hope stated above and formulates major remaining challenges in the field of mass manufacturing. This refers particularly to the material deposition rate and the workpiece quality. Another review is given by Bikas et al. pointing out main research achievement in the field of modelling additive manufacturing and identifying remaining research gaps such as verified modelling methods to control the deposit process [3]. Nevertheless, these resources help with the choice of additive manufacturing processes to be included in developments of *partial* additive manufacturing processes. As such, it is a technological basis for the work behind this article.

Hybrid manufacturing machines combine multiple production processes in one set-up [4] to enhance manufacturing quality, tool life and processing speed compared to a single process [4]. More specifically, hybrid manufacturing machines with additive manufacturing equipment are designed to overcome the limitations of pure additive manufacturing. Mostly, this is devoted to increase the surface quality, which, for example, can be found in the machine *Eclipse-RP* [5]. This machine combines additive and subtractive manufacturing in one set up. First, there is laminated object manufacturing (LOM) for additive manufacturing, which builds up a workpiece from a stack of bonded sheets. Second, the machine features a milling system, which shapes the contour of the workpiece [5]. Executing an alternating sequence of these processes, the machine builds up a workpiece in an iterative sequence. This is considered a relevant preliminary concept for partial additive manufacturing, since geometric features are added and removed iteratively. Having this concept in mind, there remains the task to overcome the limited material deposition rate, in order to maximize value creation over time. This objective is considered in the proposal stated below.

Partial additive manufacturing requires material deposition on a pre-shaped workpiece. This means that arbitrary spatial movements of the deposition process have to be realized. In contrast, current additive manufacturing machines are mostly limited to a 2D-layer based material deposition process. This is due to machining restrictions or process limitations, which is why this cannot be easily adapted for partial additive manufacturing. In order to overcome this limitation, suitable processes, suitable kinematics and suitable machine job representations have to established.

The required machine job representation in partial additive manufacturing has been approached by Yong Chen and his research group [6–8]. This research concerns, among other topics, layerless additive manufacturing processes and its visualisation in a CAD system. It incorporates CNC accumulation [6] to build features on top of the workpiece surface [7]. The process is demonstrated with a machine for multi-directional additive manufacturing by Song et al. [8]. The automated path planning used by this research group uses slicing algorithms that work in 2D or spatial path planning algorithms. The extension of such algorithms to non-planar slicing surfaces remains to be shown by research.

In summary, considerable research has been carried out to combine additive manufacturing with other manufacturing processes. Major challenges are still remaining in order to establish such conjunctions for larger series production. The first challenge to be discussed further is to define a production system with multiple machines such that it is flexible but remains productive. The second challenge is to gain a deeper technological knowledge about partial additive manufacturing. This means that the workflow to design the workpieces and to derive the production plan has to be elaborated in order to maximize its efficiency. It is proposed to employ robot-guided technologies for additive manufacturing tasks of high geometric complexity to cope with this task.

3. Incremental Manufacturing, a Proposal to Integrate Additive Manufacturing with Other Processes

In order to push additive manufacturing towards large volume production, it is proposed to combine partial additive manufacturing with other production technologies. In such a production concept, base workpieces are made in large volume production first and then finalized by partial additive manufacturing. This section discusses partial additive manufacturing in its role as additive finalization process. Afterwards, this step is generalized and formulated as a new kind of manufacturing concept called *Incremental Manufacturing*.

In partial additive manufacturing base workpieces are provided by manufacturing processes which are more productive than additive manufacturing. The base workpiece reduces the amount of features to be created by partial additive manufacturing. This means that only variant specific features are created by additive manufacturing.

Such a design optimisation is feasible in cases where the individualized workpieces out of a variant family differ only in a few key features. The result is that the additive material deposition is minimized while the geometrical flexibility of the workpiece variant design is maintained. This allows for cost-effective production of the base workpiece while the finished workpiece retains the characteristic features of an individualized workpiece. Such base workpieces can already have a high geometric complexity depending on the extent of differences between the individual variants.

The additive finalization of these complex geometries requires a production process which is capable of additive manufacturing on 3D-shaped surfaces. Such a process, in turn, requires a deposition device with higher degree-of-freedom (DOF) compared to conventional 3-axis printers. This aspect