Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

Procedia CIRP 55 (2016) 122 – 127

www.elsevier.com/locate/procedia

5th CIRP Global Web Conference Research and Innovation for Future Production

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

Klaus Dröder[a], Jakob K. Heyn[a,*], Roman Gerbers[a], Birk Wonnenberg[a], Franz Dietrich[a]

[a]*TU Braunschweig, Institute of Machine Tools and Production Technology, Langer Kamp 19b, 38106 Braunschweig, Germany*

[*] Corresponding author. Tel.: +49-531-391-7605; fax: +49-531-391-5842. *E-mail address:* j.heyn@tu-braunschweig.de

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.

Peer-review under responsibility of the scientific committee of the 5th CIRP Global Web Conference Research and Innovation for Future Production

Keywords: Mass customization; Manufacturing process; Additive manufacturing

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-

Peer-review under responsibility of the scientific committee of the 5th CIRP Global Web Conference Research and Innovation for Future Production
doi:10.1016/j.procir.2016.09.008

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 is elaborated in the case study below.

3.1. Incremental Manufacturing

It is proposed to embed partial additive manufacturing into a holistic approach for the design of production systems.This considers, for example, modular systems and flexible material transportation. The combination of additive finalization with the principle of modular systems and conventional subtractive production and joining technologies paves the way to *Incremental Manufacturing*, a generalization of the additive finalization concept. The main idea of Incremental Manufacturing is to build products by a procedure of discrete production increments. Each increment comprises one particular production step applied to the semi-finished workpiece. In this sense, a workpiece evolves in a sequence of additive, subtractive and joining processes. The challenge is to find and control a production route where products can be manufactured in a cost efficient way with high variation and production rates that range between one piece and individualized large volume production.

3.2. A Product Design Example

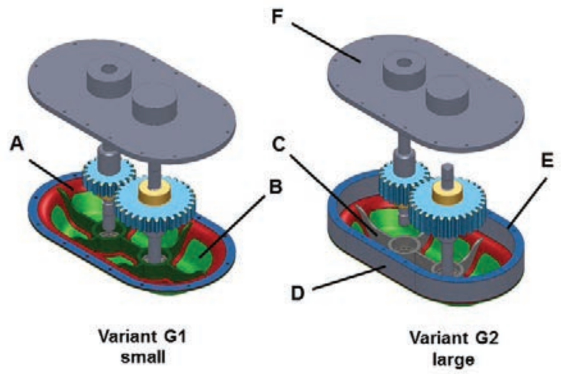

Figure 1. Design of a Gear housing build with additive finalization. (A) sheet metal frame, (B) polymer housing, (C) ribbing, (D) extension, (E) sealing, (F) cover

In order to illustrate how product design could be influenced by Incremental Manufacturing, a family of gear housing variants is considered as an example. This example consists of two variants for different performance requirements, in order illustrate the advantages of this technology. One variant is designed for high torque and one for low torque requirements. It is assumed that both variants are to be built using the same base workpieces.

The gear housing variants consist of a sheet metal frame with cut outs (A). The resulting cages (B) are then joint-formed with a plastic sheet to ensure leak tightness. Both housing variants are reinforced with a rib structure (C) on curved surfaces. The rib structure in variant 1 is made by additive plastic extrusion, while additive welding is envisioned for variant 2. The gearboxes also contain an optional extension (D) for larger gearing wheels, which is created by an additive welding process. The housings are sealed with an adhesive seal (E) and a cover (F).

The gear housing is designed with multiple manufacturing techniques in mind, for example sheet metal and joint-forming, additive manufacturing and milling. Forming processes are used for highly productive pre-production of common base workpieces and additive manufacturing is used to finalize the variants. These variants for different performance requirements can therefore be produced with low product-specific investments resulting in a productive and cost-efficient production process.

This example shows the degrees of freedom the workpiece design gains through application of Incremental Manufacturing. These new degrees of freedom motivate the implementation of such a production system.

3.3. Summary

The production of workpieces using a combination of manufacturing technologies poses multiple challenges regarding material combination, production process and flexible additive manufacturing. Process planning and process integration are two important research topics which need to be addressed. Particularly, further development of additive manufacturing towards additive finalization has to be carried out.

4. Additive Finalization: A Key Technology for Incremental Manufacturing

The concept of incremental manufacturing aims at mass customized production while minimizing the variant specific invest. This is approached by reduced use of variant-specific forming tools and by increased use of programmable production technologies. Therefore, workpiece finalization through additive manufacturing is a key technology. This technology is elaborated in the following case study.

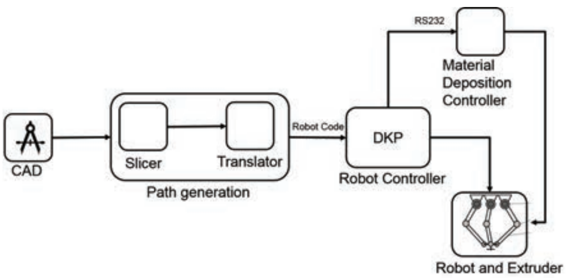

Figure 2. Control flow structure of the experimental setup used for the experiments.

4.1. Outline and Objectives of the Case Study

The case study contains experimentation with material deposition onto curved surfaces. This resembles intermediate production steps in an incremental manufacturing sequence and the finalization of base workpieces. For this purpose a robot was equipped with a fused deposition modeling extruder (FDM), see Figs. 2 and 3.

The goal of the case study is to learn the key requirements for production with partial additive manufacturing. This includes a feasible minimal solution regarding the hardware setup for partial additive manufacturing. The experimentation results provide guidelines for future machine concepts and the integration of additive manufacturing into robot-based workcells. The experimental robot presented below provides practical knowledge about the transfer of deposition processes from 3-DOF deposition to 6-DOF deposition. Besides the process and machine knowledge, the case study demonstrates geometric options for workpieces produced with partial additive manufacturing. The case study shall also identify technological shortfalls that hinder the introduction of additive finalization and -by extension-Incremental Manufacturing at the present time.

4.1.1. Robot Platform with 6 DOF

The experimental platform was developed on the basis of HEXA II [9], a robot demonstrator of the Collaborative Research Center (SFB) 562, funded by the German Research Foundation (DFG). The robot has 6 degrees of freedom, which makes it suitable for additive manufacturing on top of curved surfaces. Figure 3 shows this set-up. Being a parallel kinematic machine, the machine's actuators are located close to the non-moving base frame. This results in low inertia results and high velocity (max. 10 m/s) and acceleration (max. 10 g), which yields short cycle time of production tasks to be accomplished.

The robot is controlled by RCA562 [10], an open robot control software architecture for high performance parallel kinematic machines. This flexibility opens various ways to integrate the trajectory control in conjunction with the deposition control, so that different candidates of future machine control architectures can be compared with each other.

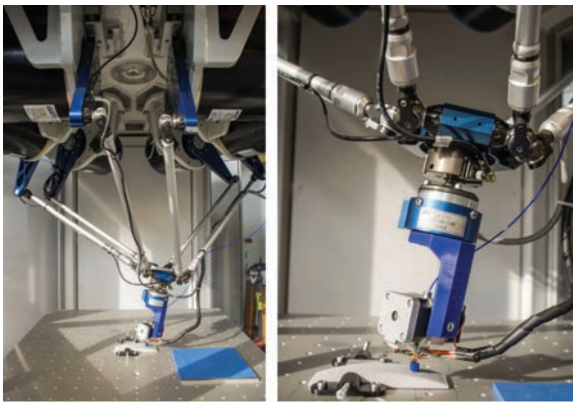

Figure 3. Parallel kinematic robot HEXA II [9] equipped with a fused depositin modelling extruder for additive manufacturing.

4.1.2. Fused Deposition Modeling Extruder

A commercial extruder for fused deposition modelling was adapted for the robot-guided additive manufacturing. An extruder controller for heating and material feed control is connected to the robot control. The interface, based on the serial RS232 protocol, is designed for interoperability with different robot controllers. This interface is minimized such that only the deposition rate as well as the robots velocity and extrusion temperature is sent to the material deposition controller. Calibration experiments were carried out, and suitable process parameters with regard to the robot velocity and acceleration, feeding rates and heating curves were found.

4.1.3. Programming Workflow and Path generation

The path generation workflow is shown in Figure 4. The Feature to be added to the workpiece is first modeled using CAD-Software. This geometric model ist then transformed such that the connection surface between the feature and the workpiece is flat. This deformend geometry can then be fed into a conventional slicing software (in our case the open-source software sic3r). The flat output of the slicing software is then transformed back into the original shape using the inverse to the first transformation. The extruder orientation is set to be perpendicular to the connection surface.

The last step of the path generation process is the generation of robot commands. The robot commands contain the extruder trajectory as well as the synchronised deposition rate. The robot program is finally compiled and ready for execution in the robot controller. This path generation process is easily portable to different robot types by changing the parsing parameters.

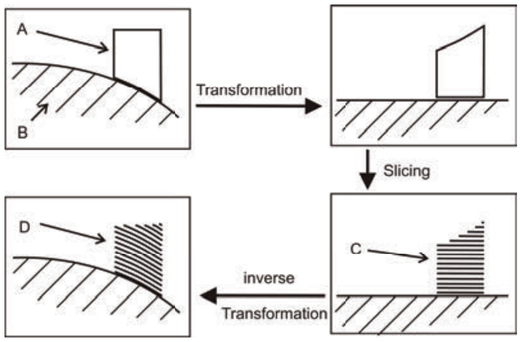

Figure 4. Path generation workflow (A: workpiece, B: feature, C: level extruder paths, D: curved extruder paths)

4.2. Experimental Procedure and Experimental Workflow

In order to evaluate partial additive manufacturing on curved surfaces, a base workpiece with curvature was designed and manufactured.Figure 5 shows the base workpiece (and also the result of the subsequent partial additive manufacturing step). In our experiments the base workpiece was produced by a commercial 3D-Printer from polylactide (PLA), this allowed the part to be made from the same material as the deposition material for the added features. Conventional manufactured workpieces made of the samen material are expected to perform similarly. The CAD-model of the base workpiece was then extended by geometric features on top of the curved surface. This was carried out multiple times to create distinct variants of the same base workpiece. In the next step, the automated path generation was invoked to generate the G-code and the robot commands based on the CAD-Data. Subsequently, the base workpieces were clamped within in the robot's workspace. A probing procedure was carried out to calibrate the base workpiece's location within the robot coordinate system. Finally, the printing process was conducted automatically.

In order to adjust the path and process parameters, preliminary experimental studies with polylactide (PLA) as deposition material took place. The following results of the parameter study were used to achieve the experimental results reported below. The robot path consists of a layer thickness of about 0.3 mm and a distance of 0.5 mm between the individual lines. The robot was moved with a constant velocity of 40 mm/s which required a constant extrusion rate of about 0.008 g/s. The temperature of the extruder was set fixed to 230C.

4.3. Experimental Outcomes and Observations

Figure 5 shows results of the partial additive manufacturing process (added geometry features in blue). In these examples, a planar structure and a rod, respectively, was added to the base workpiece curvature. The following observations were made with these and other workpieces:

- The observed layer accuracy remains slightly below that of a comparable commercial 3D-printer.
- Influence of gravitational force was not observed.
- The orientation of the extruder has an impact on the quality. This becomes obvious at the outer edge of a structure, where the orientation of the robot and the extruder requires adjustment to compensate line endings.
- No detachment was observed during the printing process, neither for the planar structure nor the rod.
- Bending radii are of consistent and high quality throughout the workpiece.
- The adhesion strength is less than the strength of the material, but strong: destructive testing breaks the workpiece at the connection seam, albeit under considerable force.

4.4. Discussion

This case study demonstrates partial additive manufacturing in an experimental set-up. In particular, it shows the feasibility of additive manufacturing on curved surfaces guided by a 6-DOF robot. This is implemented in a minimalistic control architecture, which shows the effectiveness of the approach. The following aspects were learned and derived from this study

- The path generation based on the simple projection approach is feasible for simple curved base workpieces. However, more complex surfaces may be too challenging for this approach. More complex proposals have to be elaborated to maintain the remainder of the toolchain in such situations.
- The automated path generation should be augmented by a collision detection.
- A robot for partial additive manufacturing requires high acceleration whereas, in contrast, the velocity is not very high. This may drive the development of new types of specific robots.
- The synchronisation of the extruder with the robot movement is crucial to the workpiece accuracy. Hence, dedicated interfaces should be made available in the robot control software.
- The kinematic design of the partial additive manufacturing system including its extruder has to be a compromise between workspace size, orientability, and accuracy.
- In order to minimize system changeover times, the calibration of the base workpiece with respect to the robot coordinate system should be made as efficient as possible. This aspect should be considered as early as in possible the design phase.
- The influence of gravity requires more experimental attention to decide whether the orientation of the base workpiece should be actuated.

Figure 5. Base workpiece examples printed by a commercial 3D-printer (black/grey) with blue structures added by CAD/CAM-driven partial additive manufacturing using HEXA II.

5. Conclusion and Outlook

This article presents an approach to combine additive manufacturing with other manufacturing processes to reach medium and high volume production. This approach requires a workpiece finalization process that takes advantage of additive manufacturing to fabricate variants from base workpieces. Such a process, *additive finalization*, adds the key variant features of the workpiece. This technology is generalized and embedded into the holistic manufacturing concept of *Incremental Manufacturing*.

Additive finalization is investigated experimentally by attaching a fused deposition modeling extruder to a robot. This set-up is developed to build geometry features on curved surfaces. The robotic movements are derived by an automated path generation process, where a standard slicing algorithm in conjunction with projection steps is applied to CAD-Data.

The manufactured workpiece examples on curved surfaces indicate the feasibility of the proposed process route for workpiece finalization. This workpiece finalization process is the first step for realization of the proposed Incremental Manufacturing approach. This gives the chance to develop a manufacturing system where single pieces to medium volume series can be produced with high productivity.

Moreover, it was also demonstrated that Incremental Manufacturing adds new design degrees of freedom. This can, for example, be used to build multi-material components. Another usage of these degrees of freedom is the creation of workpiece families and their efficient reproduction from base workpieces.

References

[1] Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C.B., et al. The status, challenges, and future of additive manufacturing in engineering. Computer-Aided Design 2015;doi:10.1016/j.cad.2015.04.001.

[2] Berman, B.. 3-d printing: The new industrial revolution. Business Horizons 55 2012;2012(55):155–162.

[3] Bikas, H., Stavropoulos, P., Chryssolouris, G.. Additive manufacturing methods and modelling approaches: a critical review. The International Journal of Advanced Manufacturing Technology 2016;83:389–405.

[4] Lauwers, B., Klocke, F., Klink, A., Tekkaya, A.E., Neugebauer, R., Mcintosh, D.. Hybrid processes in manufacturing. CIRP Annals - Manufacturing Technology 2014;63:561–583.

[5] Hur, J., Lee, K., Zhu-hu, , Kim, J.. Hybrid rapid prototyping system using machining and deposition. Computer-Aided Design 2002;34:741–754.

[6] Bourell, D., Stucker, B., Chen, Y., Zhou, C., Lao, J.. A layerless additive manufacturing process based on cnc accumulation. Rapid Prototyping Journal 2011;17(3):218–227.

[7] Zhao, X., Pan, Y., Zhou, C., Chen, Y., Wang, C.C.. An integrated cnc accumulation system for automatic building-around-inserts. Journal of Manufacturing Processes 2013;15(4):432–443. doi:\url{10.1016/j.jmapro.2013.05.009}.

[8] Song, X., Pan, Y., Chen, Y.. Development of a low-cost parallel kinematic machine for multidirectional additive manufacturing. Journal of Manufacturing Science and Engineering 2015;137(2):21005.

[9] Schütz, D., Budde, C., Raatz, A., Hesselbach, J.. Parallel kinematic structures of the sfb 562. In: Schütz, D., Wahl, F.M., editors. Robotic Systems for Handling and Assembly. Springer; 2010,.

[10] Dietrich, F., Maaß, J., Raatz, A., Hesselbach, J.. RCA562: Control architecture for parallel kinematic robots. In: Schütz, D., Wahl, F.M., editors. Robotic Systems for Handling and Assembly. Springer; 2010,.