

Systematic analysis of additive manufacturing for printing on semi-finished parts

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Abstract. Additive manufacturing has gained significant interest in the industry, and fused filament fabrication in particular is a promising technology. In order to use the full potential of additive manufacturing, deeper understanding in this process is necessary. For this purpose, a profound analysis according to VDI 2206 guideline (“Design methodology for mechatronic systems”) is conducted for printing on semi-finished parts with fused filament fabrication. It presents the correlation of mechanical, electrotechnical and information processing components to detect the function chain. The relevant information, energy and material flow within the overall system are identified. New functional problems emerge from the analysis. For instance, the binding of the printed segment to the semi-finished part needs to be considered. Moreover, the determination of the position and geometry of the semi-finished part poses a challenge. The analysis shows that the system needs to be expanded. To be able to print on semi-finished parts, a monitoring system, an advanced slicing software and a tempering ambience is necessary.

1. Introduction

The additive manufacturing (AM) process enables manufacturing customized parts for a wide application spectrum such as aerospace, automotive, biomedical, and electronics. It is characterized by the benefits including low cost, minimal wastage, customized geometry and ease of material change [1, 2]. The EY’s global AM survey shows that in 2019 18 % of the polled companies worldwide were already manufacturing end products using AM. For 2022, the share is forecasted to reach 49 %. [3]

Despite the wide use and increase in benefit of AM, there are still difficulties to overcome. One of the main challenges is identified as the lack of knowledge about design and production processes in AM [3]. Only few standards exist such as ISO 17296–2, 3 [4, 5], ASTM F2792 [6] and ISO/ASTM 52921 [7]. These address mainly the terminology. The complexity of AM cannot be covered yet. In order to be able to develop printed components, customized testing standards for AM processes are needed. But also for certification, an internationally recognized standard is necessary. The content could involve design, material selection and process conditions [8–10].

The most commonly used method is fused filament fabrication (FFF) [11]. The material extrusion process is used to manufacture thermoplastic components through extrusion and placing of the material layer by layer [6, 12]. Due to its ability to build functional parts having complex geometries, extrusion-based AM enables a wide field of application in lightweight construction [13, 14]. This manufacturing process is characterized by the interactions of various intellectual domains, therefore it has a high level of complexity. There are several investigations relating to the effect of printing parameters on mechanical properties of FFF printed parts [15–18]. However, the findings are only valid for the material and printer used in each study. The results cannot simply be compared regardless of their printing conditions. Next to varying parameters, another idea to exploit the potential of application, is to combine manufacturing processes. New approaches examine the fabrication using FFF merged with automated fiber placement (AFP) [19–21]. The advantages of the AFP process involve an automation of the



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production of fiber reinforced parts. These benefits can be expanded by FFF and its qualities to produce complex geometries. The combination enables the assumption of AFP guidelines, but also increases the global complexity of the system.

The objective of this study is to refine the understanding of the overall printing system for hybrid parts in a systematic way. There are several methods for the development of solutions for technical problems such as TRIZ, QFD or FMEA [22, 23]. The high grade of dependency in between components and subject areas in the FFF process lead to a complex mechatronic system. Therefore, the VDI 2206 [24] guideline “design methodology for mechatronic systems” is the selected methodology for this investigation.

2. Methodology

While the technically obsolete guidelines VDI 2221 [25] and VDI/VDE 2422 [26] deal with process models based on mechanical and electrical engineering, VDI 2206 is the complement of these. The aim is to structure the cross-domain interactions of a mechatronic system. The guideline consists of three procedure models; micro-level, macro-level and process modules. The V-model (figure 1) as a macro-cycle assists during the development of mechatronic by guiding through relevant sub-steps. Hence, the V-model is focus of interest for this study.

The model is subdivided in seven steps. The first step is to create a requirements profile, which will be the comparable figure for the final product. Subsequently, the system design serves a cross-domain solution concept. It describes logical and physical operating characteristics. The overall function is subdivided into sub-functions, to which operating principles or solution elements are assigned. During the domain-specific design, concrete solution concepts are worked out in the respective domains. The merger of the specific results takes place in the system integration to examine the interactions in the overall system. The continuous assurance of properties compares the requirements with the solution concept. An additional modeling and model analysis describes the elaborated status. Finally, the product is the output of the macro-cycle.

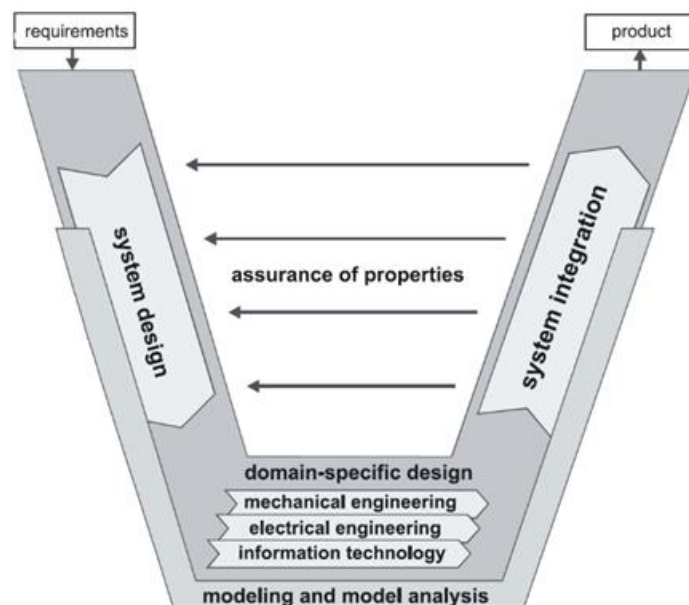


Figure 1. VDI 2206 V-model as a macro-cycle [24].

3. Results

The focus of interest within the scope of this study is the production of hybrid components. The system must be able to print on semi-finished parts.

3.1. Requirements

There are two types of requirements. Functional requirements relate to the purpose of the system, whereas non-functional requirements determine the product quality. The former includes the manufacturing of hybrid components, which are assembled from a semi-finished part and a printed segment. As a non-functional requirement, a certain component strength must be ensured.

3.2. System design

For the ability to manufacture hybrids, elements of a 3D printer are necessary. According to the sub-functions, following suitable subdivision into components emerge: build plate, filament, nozzle, print head and control box. The semi-finished part must also be provided. Regarding the component strength, the weakest point is the interface between semi-finished part and printed segment. The system needs the position data and surface geometry of the semi-finished part to know where and in which paths to print. Hence, the fusion bonding depends on the geometric deviation of the material deposition (intimate contact) and the temperature regulation (autohesion) [27]. In the case of more complex surface geometries of the semi-finished part, printing in curved layers must be possible.

3.3. Domain-specific design

Different solutions are possible for the generation of relevant geometric data. In tactile data acquisition, the sensing device palpates the object point by point. The stereoscopic system as a non-contact measurement technology is based on viewing the component from two or more camera perspectives. The subsequent determination of matches between the image pairs ultimately results in a complete 3D point cloud. This requires prior calibration of the cameras. As tactile measurement requires more time for scanning and additional kinematics, optical scanning is used in this system.

To print in curved layers, the conventional slicing needs to be adapted. Instead of printing in 2.5 dimensions, whereby the part is produced by employing layer by layer deposition, real 3D deposits the material in curved paths. This results in a layer generation in the direction of curved surfaces. Therefore the fusion bonding is ensured, the stair stepping effect is decreased and low path oriented layers are feasible. Overall, the anisotropic behaviour is exploited and the part strength increases.

Another important factor for the fusion bonding is the miscibility of the processed components. To manufacture hybrid components, the compatibility of the used materials must be ensured. In addition, the fusion bonding is temperature controlled. Therefore, a certain temperature of the components must be reached. This can be implemented by a heated and closed build space or local heating with an energy source. The concrete nozzle and ambient temperature depend on the specific boundary conditions.

3.4. System integration

The procedure of manufacturing process constitute the integration of the domain-specific solutions in the overall system. First, the semi-finished part is placed on the built plate, where it is heated and held. The monitoring system as an optical scanning device measures the surface geometry and position of the semi-finished part. The slicing software processes the data and generates a tool path in (curved) layers. The control box receives the information and passes the movement over the print head to the nozzle. The print head simultaneously heats the nozzle, which heats and conducts the filament. In the next step, the filament forms the printed segment on the semi-finished part. The hybrid is tempered by the ambient.

3.5. Assurance of properties

The monitoring system generates data about the geometry and position of the semi-finished part. The manufacturing of hybrid parts is feasible with a sufficient resolution. The slicing software must prepare and process the data into a tool path. The precision of the kinematics during deposition determines the quality of the interface. The component strength is enhanced by the temperature regulation during the printing process.

3.6. Modeling and model analysis

The interactions between components is shown in figure 2.

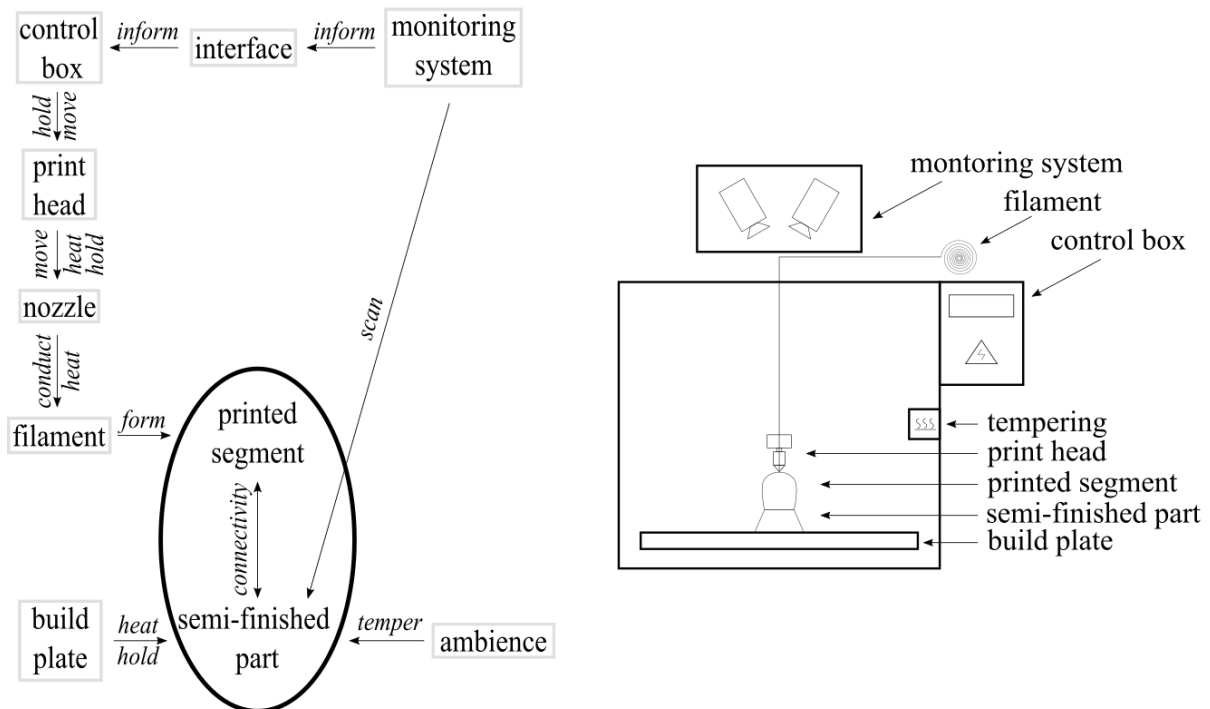


Figure 2. Functional model according to VDI 2206 [24] (left) schematic drawing of the overall printing system (right).

3.7. Product

The result of the macro-cycle is the hybrid component. The final product is the combination of a semi-finished part and a printed segment.

4. Discussion and conclusion

One of the main benefits of AM is the production of small series and individualized components. This advantage is especially used in aerospace and medical technology. Although there are some studies about functional analyses of AM, guidelines and standardization are still missing. For instance, Yusoff et al. [28] showed an improvement of the part quality using FMEA and Qianjin et al. [29] applied the SWOT methodology on product level. There is still a lack of fundamental investigations focused on the production system and its requirements. Moreover, the combination with other manufacturing processes poses a challenge. Recent studies show the feasibility of FFF with AFP. Caprais et al. [19] examined the mechanical properties of a high performance laminate manufactured with AFP and additively expanded thermoplastic. The authors conclude that the thermal treatment of the materials is the key factor to an enhanced fusion bonding. Rakhshbahar and Sinapius [20] investigate the influence of a printed continuous fiber reinforced thermoplastic composites on an AFP laminate. Consequently, the gaps as manufacturing defects can be reduced and the mechanical properties increase. Raspall et al. [21] present a design for a single station robot, which integrates AM in AFP. However, a fundamental analysis for the combination of AM with different manufacturing processes is still pending.

This study offers a functional analysis for a novel application of AM according to VDI 2206. The objective of this investigation is the analysis of AM to produce hybrid components. The complied approach enables the manufacturing of hybrid components consisting of semi-finished parts with a complex surface geometry and printed segments. First, a requirement profile is defined. The system design divides the overall function in sub-functions. The domain-specific design provides solution concepts and integrates those to the system in the system integration. The assurance of properties continuously ensures the fulfilment of requirements. A model analysis support the outcome. Following key extensions are the result for an AM system with the ability to print on semi-finished parts: a

monitoring system with an adequate precision, a slicing software with a real 3D function and a tempering ambience.

5. Acknowledgements

The authors kindly acknowledge the funding at TUM provided by the German Federal Ministry for Economic Affairs and Energy under the scheme “Central Innovation Programme for small and medium-sized enterprises (SMEs)” with the funding code ZF4004327WO9. Furthermore, the authors would like to thank IDS Imaging Development Systems GmbH for the provided camera equipment.

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