Conceptual Development of a High-Productive Fabrication System for Additive Manufactured Large-Scale Items from Arbitrarily Chosen Plastics

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Abstract

The objective of the research project is the development of a production system in order to create additive manufactured large-scale parts based on arbitrarily chosen thermoplastics. A real three-dimensional additive manufacturing process is going to be realized. It becomes possible to create items under consideration of lightweight design aspects and optimization in strength. The key-technology of the prototype is based on fused layer modeling. An offline tool automatically separates the CAD-model into partial volumes and realizes a multi-axis relative movement between extruder and shell-model. The setup utilizes three extruders to provide a huge variety of material applications and support structures. Special plastic blends are being developed and tested in order to generate items with individually desired properties like hard-soft combinations, colors and locally defined conductivities. Furthermore, it is intended to improve the bonding quality between deposited beads by tempering the extruded paths with a laser beam. Surface improvements, outlining, labeling and the functionalizing of part surfaces are objectives of this research. The final setup will be applicable for prototypes and mass production providing a part volume of 800x800x800 [mm³] and maximum weight of 25kg.

1 Introduction

Flexible manufacturing systems for the production of individualized components are going to determine modern production scenarios in long term. That also includes systems for additive manufacturing since they got the potential to substitute classical machining processes and enable the low quantity fabrication of complex geometries, possessing individual properties. Despite of their huge benefits, additive manufacturing (AM) technologies have only been asserting in (small-) series production to some extent, yet. The main focus has still been aiming especially in applications dealing with highly individualized products. [1] In AM merely a limited material availability is existent. Generally, dependent on the applied process, only one material can be processed during a build job. Hybrid material systems, consisting of more than one component and having variable properties, are currently being processed only by 3D-printing. [2] Besides that, huge deficits can be found in the stability of the process. This results in the requirement of a suitable online monitoring of the build job. Especially ensuring repeatable part properties during the production process and the monitoring of their quality plays an important role. Moreover, depending on the complexity of the part, huge data volume needs to be processed. This issue is currently faced by a segmentation of the parts and a sequentially execution by the machine. [3] An increase of process speed in AM contains a significant potential in order to decrease unit costs. Combinations of additive technologies for polymers with each other or traditional processing technologies are unexplored to a large extent. [4] Furthermore, large FDM® gantry systems do not work efficiently, particularly regarding notable expenses in case of unsuccessful production trials due to distortion or delamination. [5] At present, none of the known plastic processing AM technologies is able to produce parts fulfilling the visual and mechanical requirements of an end product and having a long lifespan at the same time. [6] [7]

2 Aims and Methods

The main focus of the project is the development of a high-productive AM system consisting of different functional modules (Figure 1). Each of these tasks requires certain expertise in engineering fields and preliminary research steps before an overall system can be designed and manufactured. Consequently, all partners need to cooperate very closely in order to combine their individual knowledge. In the end of the development process a prototype machine will be set up, commissioned and tested. The demonstrator setup will be able to overcome the common 2-1/2D process by a genuine 3D additive manufacturing technology which is going to realize the fabrication of parts optimized in strength and under consideration of lightweight aspects at the same time.

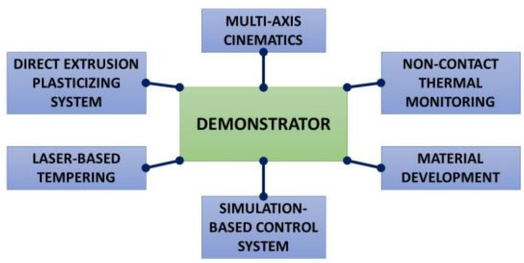

Figure 1: Functional modules of the demonstrator

The demonstrator setup will be able to overcome the common 2-1/2D process by a genuine 3D additive manufacturing technology which is going to realize the fabrication of parts optimized in strength and under consideration of lightweight aspects at the same time. Due to the development of new material combinations, the application of multi-material-systems as well as the integration of additional functional elements, a multitude of specific requirements can be integrated into plastic parts. This is realized by the combination of industrial robots and modular extrusion units based on fused-layer-manufacturing. Therefore, it becomes possible to expedite the manufacturing process and generate large-scale items which are dimensionally accurate. Furthermore, simulation and monitoring tools are able to predict the machine’s behavior and allow readjustments during the manufacturing process. In the end of the project all of these function modules will be integrated into a complex fabrication system. Subsequently, the overall system will be tested and its performance verified.

3 Current status

3.1 Process-Oriented 3D Tool Path Planning for Multi-Axis Robot Cinematics

In order to overcome the 2-1/2D – processing by a multi-axis robot, it is necessary to equip the demonstrator with an elaborate software architecture which includes the support of different processing strategies as well as an automatic creation of programs based on 3D-CAD models.

A first approach deals with the separation of the model into distinct volumes (Figure 2 left) based on information about spatial position of surfaces. This can be achieved either interactively, in terms of a selection of nods or by a determined separation path, or automatically through edge detection.

Another important requirement is the generation of flat 3D structures like the outer shell of a part. Based on the freeform surface of an STL-file, the toolpath is being calculated by equidistant elements. Inconsistencies at small radii are detected and immediately corrected by the software.

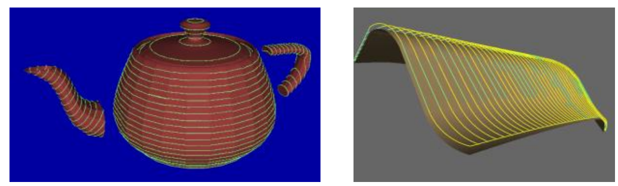

Figure 2: Separation in distinct volumes (left) and freeform surface and z-offset equidistant elements (right)

A huge task is the tool path creation for separated volumes. Especially offset-surfaces have to be calculated very accurately. The new approach exploits the subjacent toolpath. Equidistant elements aligned to the tool direction form a correct framework for the offset-plane (Figure 2 right). Consequently, the calculated surface path corresponds to the part shape of the real process.

Besides these preliminary results many other software tools are being in the process of development. This includes i. a. studies regarding the generation of support structures and suitable build up strategies. In the end, the final software program will lay the foundation for the multi-axis control of the demonstrator setup.

3.2 System Components

Glamaco Engineering GmbH is active in the field of construction of systems for the production of glass and special machines and is therefore responsible for the overall machine concept as well as the integration of the extruder assemblies (mechanical / electrical).

The basic concept for the system includes:

- 3 extruders for different feed materials

- 1 robot for the workpiece-handling

- 1 unit for the insert handling

- base frame of the overall system

The handling of the workpiece is realized by a robot equipped with a platform. The object is printed on the platform. In order to print a three-dimensional part, the platform can be swiveled in all directions by the robot (Figure 3).

A second unit used for insert handling places metallic components into the workpiece. That not only leads to a stiffened structure of the printed item but also provides functional elements.

Figure 3: Robot for workpiece-handling

Direct Extrusion Plasticizing System

As a member of the general consortium, the Technische Universität Ilmenau deals with the material-dependent process development of the additive manufacturing system. The attention is paid to the characterization of the extrusion and layer-based process in order to ensure a stable and accurate end-contour process control even at high application rates.

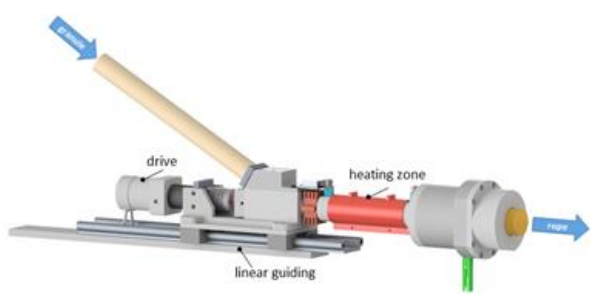

Figure 4: Plasticizing system

For the basic design of the process, a plasticizing system (Figure 4, Figure 5 (1)) was developed, which is able to process standardized plastic injection mold granules directly. Thus, it is possible to avoid the use of previous filamentary feed materials. The resulting material cost advantage can be used to favor a profitable production and thus, establish the process for further application areas. Furthermore, the processing of granular materials allows a selection of a significantly increased field of verified basis materials.

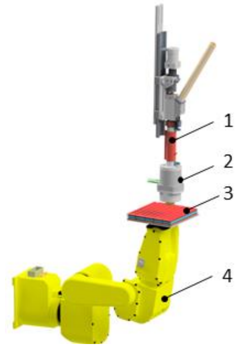

Figure 5: Complete factory system

The system (Figure 5) was built in modular design in order to be able to react flexibly to material-dependent system adaptations and to minimize set-up times. For a defined strand separation, the assembly was provided with an additionally separation unit. Thus, a modified needle shut-off nozzle unit (2) is connected downstream of the outlet of the plasticizing unit, which allows time-controlled to separate the molten plastic strand. So, an unintentional thread formation during the building process can be completely prevented. The entire system interacts with a six-axis articulated robot (4), which is used for positioning the heated building platform (3) and permits a completely three-dimensional strand application due to its kinematic movement range. (cf. chapter 3.1 Process-Oriented 3D Toolpath Planning)

In the further course of the project, a material-specific analysis of the layer-based process is planned. Reachable process limits will be identified, as components will be geometrically and mechanically characterized as a function of the joining temperature. Finally, all collected information will be combined in a layer model and a functional machine will be realized.

Laser-Based Tempering

In order to improve the bonding quality between the deposited beads a hybrid process is being developed. For that approach an experimental assembly (Figure 6) has been setting up at the Ernst-Abbe-Hochschule Jena since the beginning of the project. The machine concept aims to merge Fused-Deposition-Modeling (FDM®) with an additional laser application to temper the extruded beads during the printing process. For this purpose, a former milling machine (I) has been converted into a 3D-printer by replacing the milling spindle by an extrusion plasticizing system (II) and implementing a CO_2-laser (III).

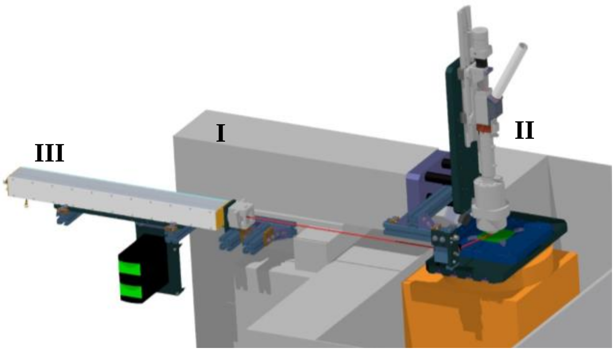

Figure 6: Experimental setup of the hybrid-machine

After the implementation of all components and the commissioning of the overall system, laser and machine parameters are going to be examined in order to gain a reliable process window. The tempered extrusion paths are going to possess a stronger bonding, denser microstructure and decreased delamination under continuous load. Hence, parts should be able to provide an improved tensile strength of up to 95% compared to injection molded parts. Those findings will provide a new approach regarding additive manufacturing of end-use prototypes and thus, lay the foundation for new applications during the process development cycle.

3.3 Simulation-Based Development of the Design of an Innovative Control System for an Additive Manufacturing System

In this joint project, the Fraunhofer IFF is working on the development of the control system and simulation for demonstrator system accompanying development them. The components of the innovative control system design include component control, motion planning and machine monitoring and operation. In this subproject, the simulation will be coupled with the machine controller and a safety specification that prevents collisions in work spaces will be developed. Also workpieces and materials will be incorporated in all of the operations and the real-time capability of the models created will be demonstrated under real conditions.

The integrated simulation and software tool VINCENT developed by the Fraunhofer IFF is being used to develop the control system for complex manufacturing operations (Figure 7). This new integrative approach to motion planning and event simulation makes it possible to test geometry and function before manufacture of the system commences. Connecting the virtual model of the system with the real control system online makes it possible to identify potential collisions between different system components and the complex part being manufactured before a task is executed. The software tool interconnects established systems and standards and easily imports CAD data (STEP files).

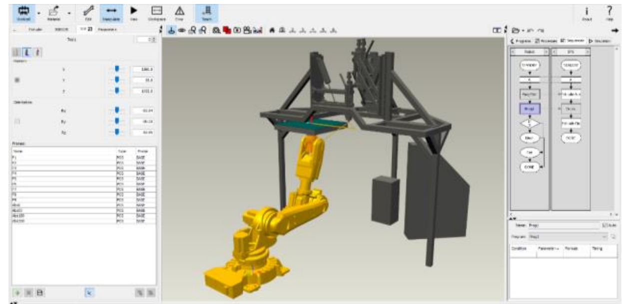

Figure 7: Simulation based development with VINCENT

As the project proceeds, the Fraunhofer IFF will modify and optimize the control system modules and the respective technical specification of the electrical components (drives, sensors, control loops, etc.) factoring in the extruder's final gantry design and the insert handling elements. Another important objective is reliable detection of any potential collision zones and collision control in real time.

3.4 Development and Modification of Plastic Resins for the Part Fabrication

Granula is a specialized supplier of color, functional masterbatch and compound solutions for plastics and thus, responsible for the development of special materials in this project. In close cooperation with the partners TU Ilmenau, 3D Schilling and EAH Jena special polymers and additive grades have been developing. Based on different polymers material concepts are in a constant process of design and testing. Besides a good material flow in the extrusion line and a reduction of the heat coefficient, a consistent process ability over a wide temperature range is desired.

Figure 8: Parts made of ABS showing good bonding quality (Image source: TU-Ilmenau)

Initially, a characterization of the developed extruder became necessary. After examining the extrusion process of different sized pellets it was found that the plasticizing unit is capable to process any standard pellets without additional modifications. Due to this important result the production of new blends is not impeded and no special machinery is required for further research. Moreover, bonding qualities between the polymer layers were investigated. A very good interlayer connection between ABS beads in z-direction is achievable at an interpass temperature of 180°C (Figure 8). On the other hand, defects like air pockets lead to a reduced bonding quality (Figure 9) and are therefore being investigated further.

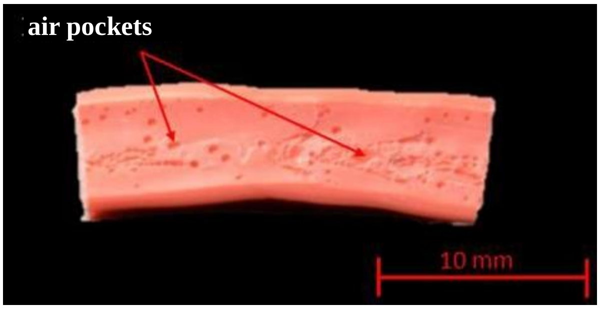

Figure 9: Parts made of ABS showing interlayer defects (Image source: TU-Ilmenau)

Furthermore, several concepts were made in order to design multi-material parts combined of different polymers as well as components having hard and soft areas. Preliminary results show that especially inner tensions lead to stress cracking. Hence, one or more SEBS/TPE will be examined in order to apply them as a linking material. In addition, first attempts of extruding polymer foams were made (Figure 10).

Figure 10: Extruded polymer foam (Image source: TU-Ilmenau)

In consequent steps, special resins for water or alcohol soluble support material are going to be developed and examined in future investigations. At the moment, first studies focused on water soluble PVA mixed with and without release agents. Upcoming studies will consider the increase of the glass transition temperature of PVA by adding certain additives as well as permanent antistatic agents.

4 Preliminary Results and Prospects

As presented, the research consortium has been dealing with tasks in very different engineering fields for the first half of the project. Since the most important and influential decisions in a machine-development-process have to be considered in the beginning, the current state provides merely first research results and the main concept of the overall system as well as its subsystems (Figure 11).

Among those findings are first approaches for handling multi-axis robot cinematics, the investigation and development of the main demonstrator components regarding extrusion, clamping, noncontact temperature measurement as well as an overall concept of subassembly arrangements and handling systems. Additionally, a simulation-based control system has been developed and many modifications of plastic resins for the part fabrication have been conducted, examined and tested. Upcoming investigations regarding the laser-based tempering of plastics will provide the knowledge whether mechanical properties of printed elements can be improved. In case of a significant conversion of the parts' mesostructure, drawbacks of the orthotropic behavior could be overcome and therefore, printed objects become more comparable to injection molded parts. Further developments will also continue research in the individual fields of each partner as well as focus on the demonstrator setup, its commissioning and subsequent optimizations.

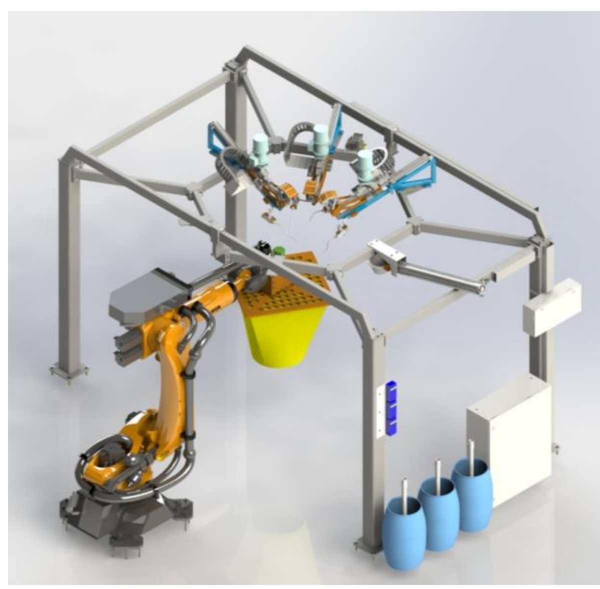

Figure 11: CAD-Layout of the demonstrator setup (Image source: Glamaco)

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