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KNOWLEDGE-BASED MATERIAL PRODUCTION IN THE ADDITIVE MANUFACTURING LIFECYCLE OF FUSED DEPOSITION MODELING

C. Auth*, D. Borstell**, R. Anderl*

*Department of Computer Integrated Design (DiK), Technische Universität Darmstadt, 64287 Darmstadt, Germany
** Faculty of Engineering, Koblenz University of Applied Sciences, 56075 Koblenz, Germany

Abstract

The additive manufacturing (AM) lifecycle starts with the material production. This phase has an impact on the AM process and its quality. Nowadays, information concerning material production is not connected to the manufacturing process or the manufactured component. Increasing digitalization enables data acquisition, handling and management. Nevertheless, an integrated data concept for all AM lifecycle phases has not been realized yet. Using information collected during the material production to evaluate component quality and process stability is a huge research gap. Therefore, this paper deals with establishing a data connection between material production and manufacturing phase. Based on the explanation of the AM lifecycle, the identification of key influence factors and their interdependence a concept for a knowledge-based material production in the AM lifecycle of fused deposition modeling is developed. To prove the rationale behind the knowledge-based approach the interdependence between two exemplary key factors is then evaluated experimentally and the result is discussed. The implementation and validation phases contain the sensor plan for the material extruder and the experimental examination of the effects of filament diameter changes on product quality.

Introduction and Motivation

The increasing digitalization enables the collection, analysis and storage of data in production processes. There are different goals and business cases to use data in context of Industrie 4.0. One possibility is a tracking and tracing application to monitor the location and production progress of a part. Another possibility to use process data is predicted maintenance. The main aim is a reduction of unexpected machine breakdowns and therefore, an optimization of process stability. Furthermore, activities of Industrie 4.0 help to achieve high quality levels. End controls of the part might be reduced through permanent data collection and analysis. [Pla14] The new business models are not implemented in the AM sector. An integration of the capabilities of Industrie 4.0 in the AM lifecycle can contain high potentials concerning process and quality optimization.

In the field of AM, no standards for data collection or analysis exist. AM machine producers start to use collected data to optimize or monitor the production process. For example, the company Arcam uses a camera system in their machines to detect defects in components [Arc18]. An overall concept and an implementation of a holistic and long-term data management for AM machines or processes does not exist yet. Furthermore, no information transfers between the different phases of the lifecycle have been established. This lack of data acquisition, handling and management is the motivation for the development of a concept and the implementation of a knowledge-based material production in the additive manufacturing lifecycle of fused deposition modeling (FDM). Therefore, important information of the material production process needs to be identified and a measurement concept needs to be developed. The collected information is transferred to other phases of the FDM lifecycle, especially to the phase of product manufacturing. With the help of the information, the product manufacturing phase can be optimized. The relations between the material production and the product manufacturing phase are examined in the concept and implementation chapter of the paper. To develop a concept for knowledge-based material production, the AM lifecycle needs to be explained. Based on that, influence factors of material production on product quality and process stability are identified. The identified factors serve for the concept development.

In the state of the art, the AM process chain and lifecycle are explained. The different phases of the AM lifecycle are explained for FDM. This helps to identify the influence factors of material production on the product and process quality in the concept chapter. Besides, the concept chapter deals with the development of the sensor plan to measure or determine the influence factors. To prove the choice of influence factors, the implementation chapter deals with the installation of a demonstrator of the FDM lifecycle. Furthermore, a hypothesis concerning the correlation of filament diameter changes and part stability is evaluated experimentally. The paper ends with a conclusion and a short outlook.

State of the Art

An elementary background for the knowledge-based material production is the AM process chain with the three phases pre-, in- and post-processing. During the pre-processing, the machine is prepared. With the data transformation, the native CAD data is converted into the STL (Standard Tessellation Language) format, which is the common data format used with most of the printer software systems today. After this, the part orientation and positioning takes place. Afterwards support structures are generated, if they are needed. This depends on the AM manufacturing method and the capabilities of the printer. The last step of the pre-processing is the slicing. After the pre-processing, the in-processing follows with the manufacturing process. Furthermore, the unloading and part removal are included in the in-processing. The post-processing includes the removal of additional powder or the removal of support structures, depending on the AM method. Besides, the improvement of the component characteristics is part of the post-processing. [Aut18, Gib10, Ver14] Figure 1 shows the pre-, in- and post-processing as overview.

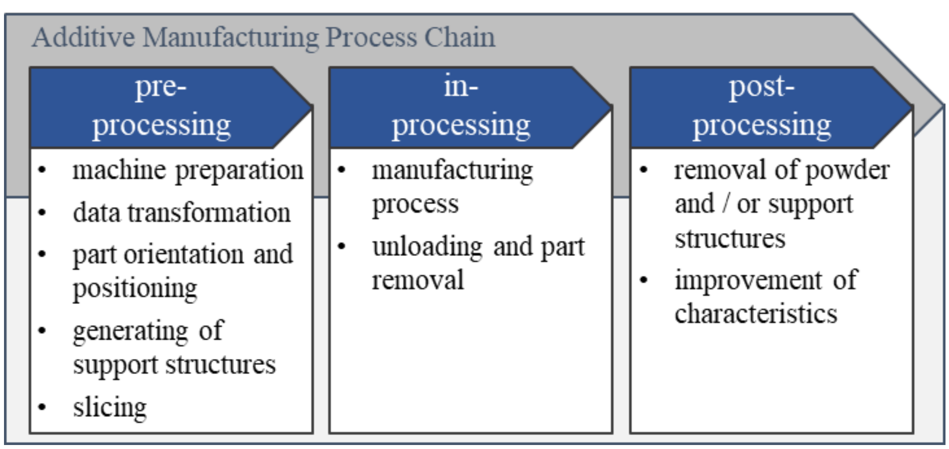

Figure 1: Overview of the AM Process Chain [Aut18]

The phases of the AM process chain are optimized to increase the achievable quality of the manufactured part. During the pre- and in-processing, the adjustments of the approximation of the component geometry and machine parameters are essential to produce a certain quality. Faults caused during pre-processing (e.g. through wrong part orientation or selection of a too tight approximation accuracy) will have a negative effect on the component´s surface quality and mechanical rigidity. Arndt et al. (2015), Gurpal (2014) and Kirchner et al. (2010) have shown these influences with the help of experimental testing and surface examination. Besides, different AM machine producers connect information of the pre- and the in-processing to minimize reject rate and to avoid mistakes [Eos18].

The integration of the AM process chain into the AM lifecycle can help to maximize product quality. The AM lifecycle starts with the new material extraction. In case of FDM, mineral oil serves to produce the plastics. In the second phase of the material production, the new raw material is transferred into a suitable shape. The raw material is extruded and coiled as filament on a reel. The third phase is the product development consisting of the four sub-phases product planning, product design, work preparation and product manufacturing. In the phase product development, the component geometry is developed depending on the existing requirements for the part. Caused by influences of the AM method on the component geometry, the selection of a certain AM method needs to be frozen at this time. After the product design, the work preparation as pre-processing starts. During the following product manufacturing, the in- and post-processing takes place. The product distribution follows the product development. At this time, the component becomes the property of the user for the following product use phase. The last phase is the product end of life. Depending on the chosen material or AM method, the product can be recycled or has to be disposed. [Aut18] Figure 2 shows the AM lifecycle with the integrated AM process chain as overview.

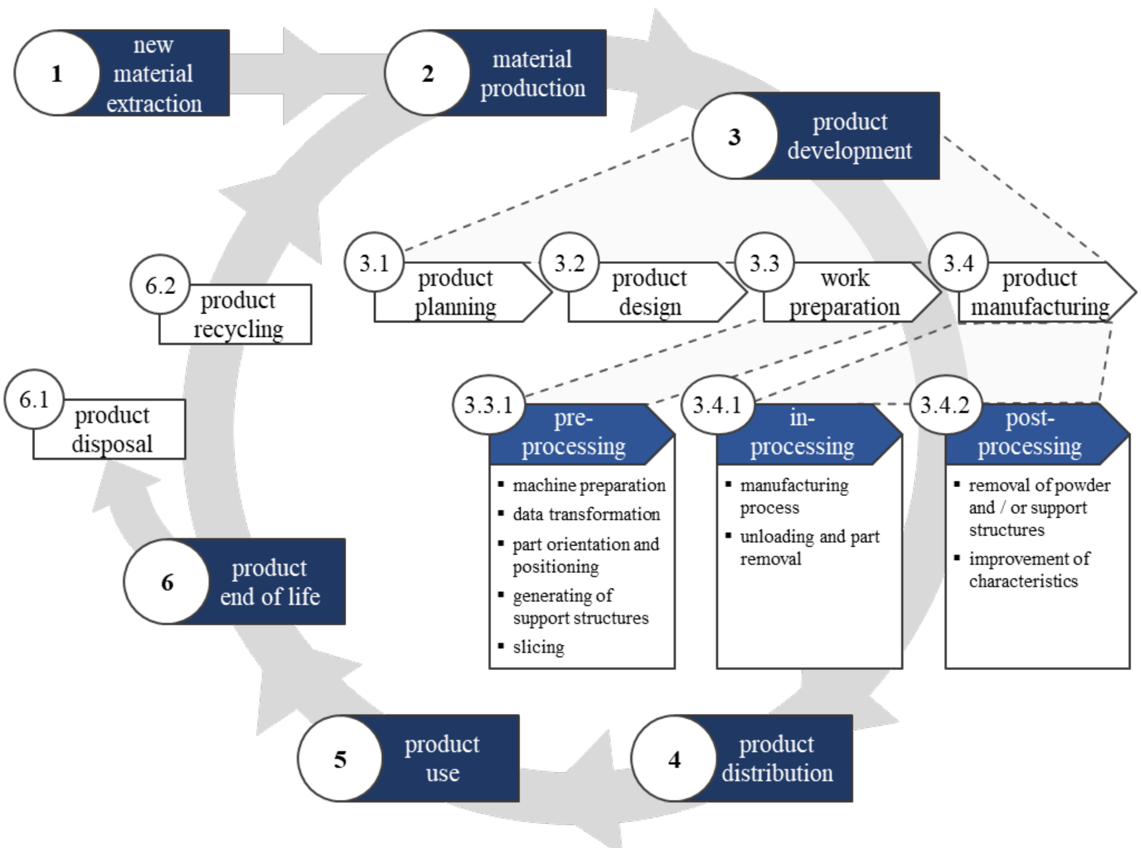

Figure 2: overall AM lifecycle with integrated AM process chain [Aut18]

After briefly explaining the AM process chain and lifecycle, the following chapter deals with the concept for a knowledge-based material production. For this concept, the phases material production and product development with the integrated AM process chain are most important.

Concept

The core of this concept is the connection of information of the material production phase to the product manufacturing phase to increase component quality and process stability. In the first part, the phase of material production is described. After this, requirements on the kind and amount of collected data are defined. The next step is the description of the influence factors and their connection. This chapter contains a hypothesis, which is tested experimentally in the implementation and validation chapter.

The phase of material production comprises the transformation from the raw material to the filament, which can be used on FDM printers. To realize this transformation, an extruder is necessary. The raw material can be inserted as granulate material. The sorting accuracy has to be assured to prevent defects in the filament. In the extruder, the granulate material is compacted and heated up to be extruded through a nozzle. The new extruded filament needs to be cooled down to conserve the shape. After this, the new produced filament can be stored on a material reel. In this form, the material can be used for printing or stored properly.

To guarantee the quality of the filament and to optimize the whole production process of a component, various data needs to be collected, analyzed and stored for long-term use. There are requirements concerning the nature and the amount of this data. These requirements help to ensure that all relevant information for the following lifecycle phases are collected. The following requirements are important:

- There has to be a trade-off between the amount of the collected data and the information, which can be extracted with the help of the data.
- Depending on the kind of data, it can minimize the amount of data if key performance indicators are calculated or only the changes of the data stream are documented.
- A proper data format has to be chosen for data acquisition, data communication and data storage.
- To monitor data, to indicate correlations and to identify extremal values a database needs to be implemented, where the collected data can be managed.
- To transfer data into the database communication between the database and the sensors or the machine system has to be realized.

These five requirements have to be fulfilled to enable a knowledge-based material production. Besides these requirements, potential influence factors are defined. The influence factors can have an impact on the process. The influence factors are data or measurements from the machine or systems. To guarantee a high quality of the produced filament and to achieve better process stability at all, these factors, which influence the quality and stability, have to be measured and monitored. Important influence factors of the material production are:

- Granulate material sorting accuracy: the granulate material sorting accuracy is important to ensure. If foreign particles get into the new filament, they might cause breaking of the new filament, plug up the extruder or printer nozzle or minor the quality of the newly built component.
- Granulate material particle size: the granulate particle size needs to be smaller than a defined size. Exceeding this size can cause an extruder stop, because big particles block the mechanical handling of particles to the extruder nozzle.

- Temperature of the nozzle: the temperature of the nozzle must not exceed or go below a certain temperature range. Higher temperatures can have negative influences on the characteristics of the plastics. Lower temperatures can prevent the fusing of the particles, which will cause breaking of the filament.
- Diameter of the new produced filament: the diameter of the new produced filament needs to be in a determined range. Exceeding the diameter the nozzle of the printer may lead to blockage of the nozzle. If the diameter underruns the range, defects may occur in the new build component. The single layers do not have enough material to fuse together. Delamination can be a consequence.
- Cross section of the new produced filament: the cross section of the new produced filament has to be round or nearly round. If the cross section differs much, the printer might not be able to insert the filament.
- Length of the filament rolled up: the length of the filament is an important information for the printing process to ensure that the part can be built completely in the printing process.

The granulate material sorting accuracy, the granulate particle size and the temperature of the extruder nozzle directly affect the quality of the filament and the production process of the filament. The highest impact on the printed part itself has the diameter of the filament. Imperfections in the filament might affect the part quality directly. To evaluate the correlation of filament diameter und component quality, the following hypothesis is made:

Hypothesis: *The diameter of the filament affects the printed part directly concerning surface quality and part stability.*

This hypothesis is tested experimentally in the following implementation and validation chapter. If the hypothesis can be confirmed, the motivation for a knowledge-based material production opens up and it is given reason for data acquisition, handling and storage.

Prototype Implementation and Validation

This chapter serves for the implementation of the concept and for validation of the hypothesis. To test the hypothesis the material production and product development are realized in a demonstrator as two lifecycle phases. Within the experiments, exemplary parts are printed with manufactured filament. The parts are tested experimentally in a tensile test to investigate the influence of filament diameter changes and to examine the hypothesis. An extruder represents the material production. This machine was developed and built at the Department of Computer Integrated Design at TU Darmstadt, named *DikXtruder*. The extruder can be used with new granulate material or with shredded scrap parts. A funnel helps to insert the new or recycled granulate material into the mechanism, that condenses the granulate material and heats it up for the extrusion. After the extrusion, a water basin helps to cool the new filament down. The filament is rolled up on a material roll at the top of the extruder. A sensor to measure the filament diameter has been integrated. Furthermore, the temperature of the nozzle is measured. The length of the filament is calculated by counting the steps of a stepping motor. There is a light barrier to guarantee the availability of granulate material in the funnel. Besides, there is a sensor to check if there is still water inside the water basin. The granulate material sorting accuracy is verified before the material production starts. For recycled material, the different materials of the scrap parts are determined. With a separation of colors, a mono-material granulate can be produced. Bought granulate material is checked in visual testing. Figure 3 shows the *DikXtruder* and the sensor layout plan for data acquisition.

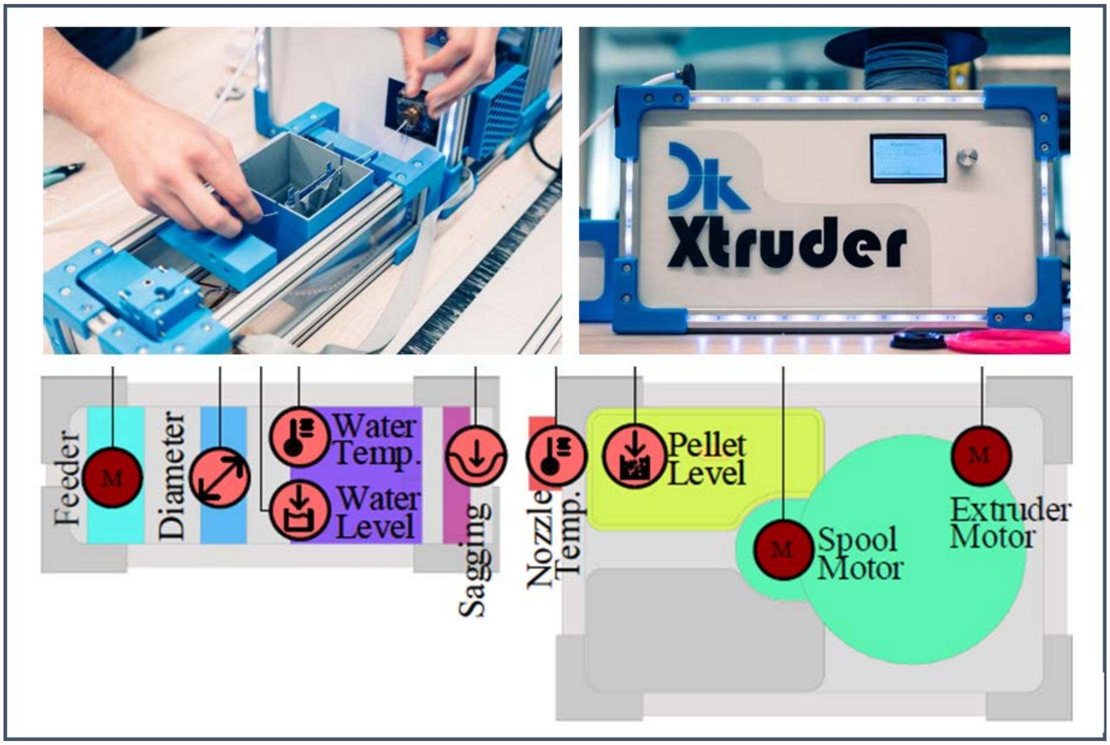

Figure 3: Setup and sensor layout plan for the extruder *DikXtruder*

Different printers and a computer for virtual product development represent the product development phase. The different printers, which are used to manufacture the exemplary parts, are shown in the experimental set-up.

Design of Experiment

The main aim of the experiments is testing the hypothesis. To test the effects of diameter changes in the filament on the surface quality and the stability of the printed part, several exemplary parts have to be printed and their quality has to be examined. Figure 4 shows the process of the experiment in an overview.

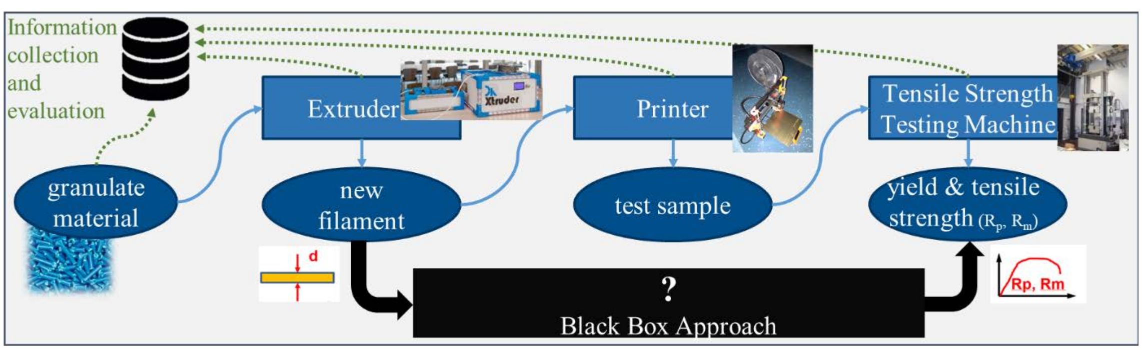

Figure 4: Design of experiment

The approach here shall be to create one black box looking only at the filament diameter as input and on the quality of the part itself as output, trying to relate these to each other. The quality of the output shall be measured by determining yield strength (R_P) and tensile strength

(R_m) of the sample. In reality, there are several mechanical transformations of the filament between the reel and the printed part, which all have an influence on the quality of the product:

a) The mechanical drive force-feeding the filament into the tube before the hot end.
b) The "Hot End" consisting of a tube with the same diameter as the filament diameter before the smaller nozzle.
c) The build-up of the part influenced by the setting of the printing parameters, e.g. the printing-orientation of the part.

Experimental Set-Up

***Hardware*:** To manufacture the samples a FDM printer type PRUSA i3 MK3 is used. Some reference samples are printed using an ULTIMAKER 3 – both located in the Research Lab for Additive Manufacturing at Koblenz University of Applied Sciences. In order to test the resulting overall quality of the manufactured test samples their yield strength and tensile strength have to be measured using a 60 t Tensile Strength Testing Machine also located at Koblenz University of Applied Sciences.

***Geometry of Printed Samples*:** The geometry of the test samples corresponds to DIN 50125, Form E. In order to meet the requirements of measuring tensile strength and in order to fit the attachments of the testing machine the dimensions presented in figure 5 are selected.

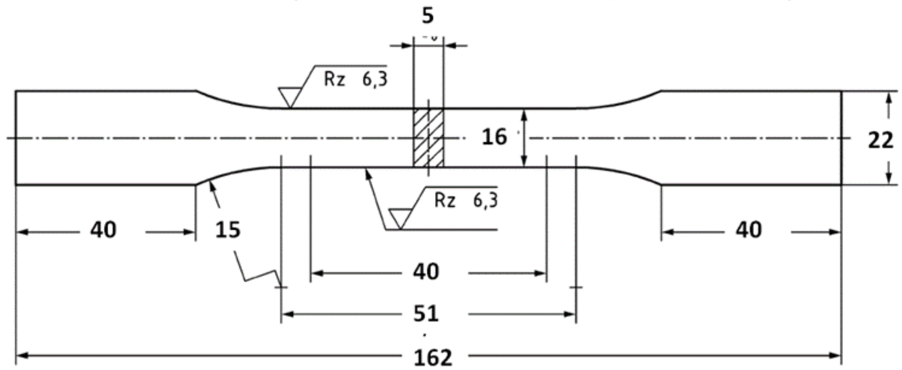

Figure 5: Sample Geometry

Material: To evaluate the influences of diameter variations on the printing process and component quality and stability, the test filament has to show some variations. Therefore, test PLA-filament was extruded using the *DikXtruder* extruder located at TU Darmstadt with a nominal diameter of 1.5 mm with variations of -0.4 / +0.25 mm. Figure 6 shows exemplary diameter variations of the produced filament. For comparison, standard material has diameter variations of +0.05 / -0.05 mm.

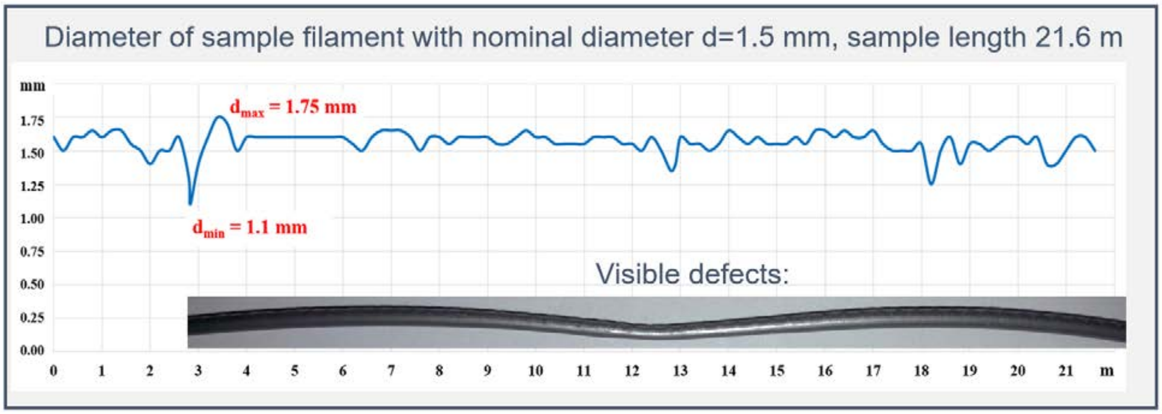

Figure 6: Typical diameter variations and visible defects of filament

Experimental Procedure

In order to evaluate the effect of diameter variations on the quality of finished parts different sample variants were printed. All tested samples were printed on the PRUSA i3 MK3, which is designed for 1.75mm diameter filament. The following variants in table 1 were printed.

Table 1: Sample Variants

Variant No.	Filament diameter [mm]	Diameter setting for slicing [mm]	Printing Orientation
1 a	1.75	1.75	lying flat
1 b	1.75	1.75	upright
2 a	1.5	1.75	lying flat
2 b	1.5	1.75	upright
3	1.5	1.5	lying flat
4	1.75	2.04	lying flat

Variants 1a and 1b: These reference samples were printed with original PRUSA-1.75mm filament sliced with 1.75mm diameter for a fill ratio of 1.0. In order to evaluate the effects of the interlamellar bonding samples were printed lying flat (variant a) and standing upright (variant b).

Variants 2a and 2b: The variants 2a and 2b were printed using 1.5mm filament sliced with 1.75mm diameter. The effects of underextrusion can be clearly seen during printing. Lower strength should be expected due to the reduced fill ratio caused by the 1.5 mm filament. However, the surface layers look unsuspicious. An enlarged view reveals some gaps in the structure as shown in figure 7.

Figure 7: Internal sample structure, surface and enlarged view of surface of variant 2a and 2b

In order evaluate the effects of the interlamellar bonding samples were also printed lying flat (variant a) and standing upright (variant b). In comparison to variants 1a and 1b the following two questions can be answered:

- What is the effect of using a significantly smaller nominal diameter: 1.5mm instead of 1.75mm?
- What is the effect of significantly higher diameter deviations than using generic or original filament?

Variant 3: Variant 3 would have been the ideal comparison to variants 2a and 2b, having the same nominal fill ratio of 1.0. However, no samples could be printed because of mechanical failures in the feed drive and clogging before the hot end. The fact of a failure before a sample could be printed is a significant information regarding a knowledge-based system.

Variant 4: In order to be able to compare the effects of using 1.5mm filament and 1.75mm filament, samples were printed using the same fill ratio as variants 2a and 2b (0.73) but using original 1.75mm filament. Therefore, it is sliced with 2.04 mm.

Table 2 gives an overview of the different variants.

Table 2: Summary of Sample Variants

No.	Filament diameter [mm]	Filament source	Diameter setting for slicing [mm]/ fill ratio	Printing orientation	Filling orientation	Remarks
1a	1.75	PRUSA	1.75 / 1.0	lying flat	45° / 45°	Different fill rate compared to 2a / 2b, because of different filament diameter
1b	1.75	PRUSA	1.75 / 1.0	upright	45° / 45°	
2a	1.5	DikXtruder	1.75 / 0.73	lying flat	45° / 45°	Same fill rate as 4 Different fill rate compared to 1a / 1b, because of different filament diameter
2b	1.5	DikXtruder	1.75 / 0.73	upright	45° / 45°	
3	1.5	DikXtruder	1.5 / 1.0 see remark	lying flat	45° / 45°	Fill rate greater than 1.0 due to diameter deviation

						to larger diameters caused clogging of hot end
4	1.75	PRUSA	2.04 / 0.73	lying flat	45° / 45°	Same fill rate as 2a / 2b

Experimental Results

After printing the different sample variants, the testing follows. Each variant is tested in a tensile test. The following tensile stress values were reached, summarized in table 3.

Table 3: Tensile Stress Values

No.	Filament diameter [mm]	Diameter for slicing [mm]	Printing Orientation	Tensile Stress [MPa] 5 Samples each					Average [MPa]
1a	1.75	1.75	lying flat	34.9	35.9	36.7	35.4	35.4	35.7
1b	1.75	1.75	upright	25.4	26.3	24.2	24.5	24.9	25.1
2a	1.5	1.75	lying flat	18.9	20.5	18.7	18.4	21.2	19.5
2b	1.5	1.75	upright	11.4	11.4				11.4
3	1.5	1.5	lying flat	X	X	X	X	X	X
4	1.75	2.04	lying flat	16.1	16.2	15.8	15.8	18.5	16.5

Figure 8 shows the average tensile stress values for the six variants in an overview.

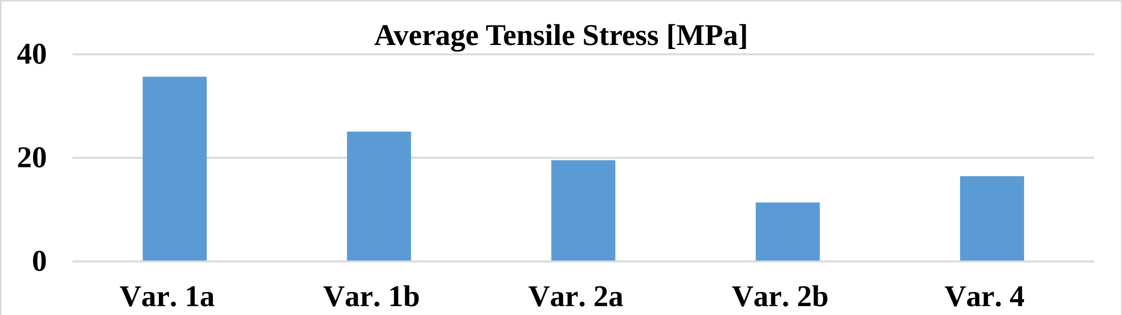

Figure 8: Average Tensile Stress Values

As expected tensile stress is the highest for the sample printed with original "high quality" filament and a fill rate of 1.0. Standing up printed samples have a lower tensile stress that the samples printed lying flat. However, it is surprising that variant 4 – made from original 1,75mm filament – shows significantly lower tensile stress values that variant 2a, which has been made from 1.5 mm filament.

Evaluation of variant 3: Samples could not be printed because of mechanical problems "within the black box". Clogging of the tube before the hot end regularly caused the filament to be jammed up in the mechanical drive after about 30 to 45 minutes of printing time. The phenomenon of a cold reverse flow, which will eventually clog the nozzle, is well known. The influence of the diameter on the quality of the printed part is that we do not get a sample at all – a significant fact for a knowledge-based system. Figure 9 demonstrates the problems.

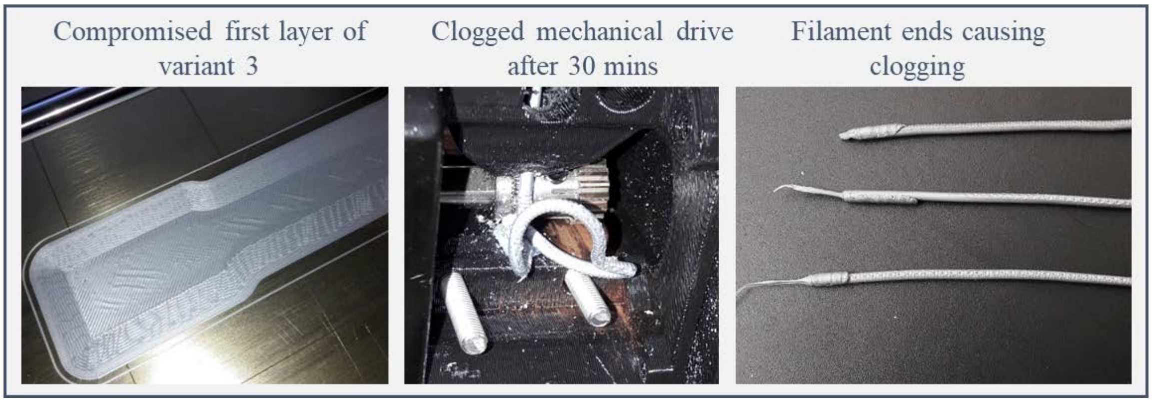

Figure 9: Mechanical problems printing variant 3

Evaluation of variants 4 and 2a: It allows the comparison of equal fill rates but different filament diameters. Our expectation would be that variant 2a should have the same tensile stress values as variant 4, as the fill rates are the same. 2a might have lower tensile strength due to greater diameter deviations of the filament. However, we see a 20% greater tensile strength for variant 2a! The diameter seems to have an influence. Figure 10 presents the tensile strengths in an overview.

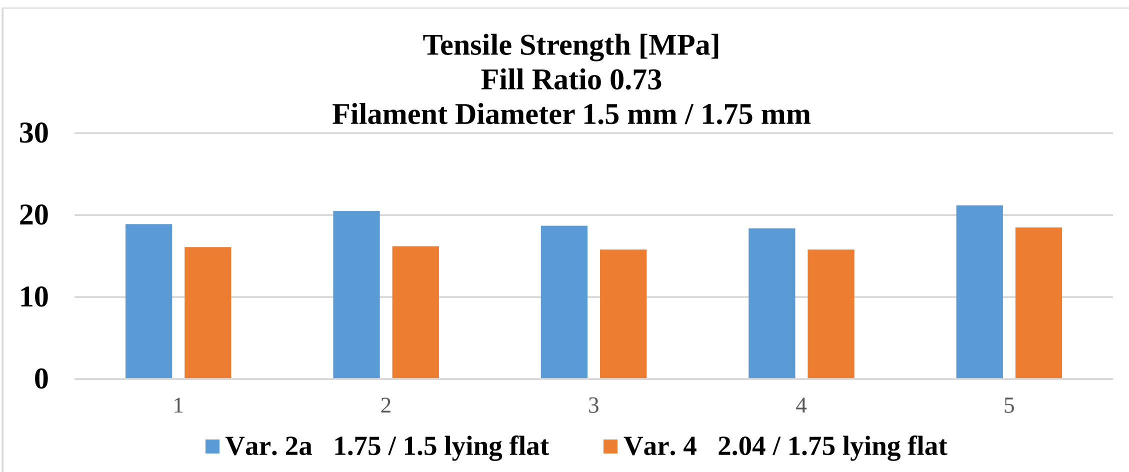

Figure 10: Comparison variants 2a and 4

Conclusion and Outlook

The progress in the field of Industrie 4.0 and digitalization enables new business models and further possibilities in process optimization. A knowledge-based additive manufacturing offers chances to increase the process stability and the component quality. Therefore, a method for a knowledge-based material production is developed. The material production is the second phase of the AM lifecycle after the new material extraction. After this, the product development follows with the AM process chain. The next phases are the product distribution, product use and product end of life with recycling or disposal.

After optimizing the phases separately, an overall optimization of the lifecycle includes new potentials. Requirements for a knowledge-based material production are the right amount and kind of data, a proper data format, communication and database. Important influence factors of the material production are granulate material sorting accuracy and particle size, temperature of the nozzle, diameter and cross section of the new filament and the produced length. A hypothesis dealing with effects between the filament diameter and the surface quality and part stability of the new printed part is developed and tested experimentally. Therefore, the phases of material production and product development are realized in a demonstrator. A test geometry is printed in different variants. Some of the variants are printed with self-extruded filament, which has a high deviation of filament diameter. Implemented sensors in the extruder measure the diameter of the new produced filament. Therefore, the information can be connected to the manufactured part. The tensile strength of the variants is measured using a Tensile Strength Testing Machine. The tensile strength of variants printed lying flat is generally higher than standing upright. The fill ratio has an effect on the tensile strength of a part. The tensile strength of variants printed with self-extruded filament with a fill ratio of 0.73 is 20 % greater than the tensile strength of a printed part with original filament with the equal fill ratio. This correlation should be tested in further experiments. Besides, smaller diameter variations have to be examined to find out maximum deviations.

References

[Arc18] **Arcam EBM (2018):** Process Validation Tools. Online achievable: http://www.arcam.com/technology/electron-beam-melting/process-validation-tools/

[Arn14] **Arndt, A.; Hackbusch, H.; Anderl, R. (2015):** An algorithm-based method for process-specific three-dimensional nesting for additive manufacturing processes. In: 26th Solid Freeform Fabrication Symposium 2015, 10.08.-12.08.2015, Austin, Texas.

[Aut18] **Auth, C.; Arndt, A.; Anderl, R. (2015):** Development of a concept for a holistic knowledge-based additive manufacturing over the entire lifecycle. In: IFIP 15th International Conference on Product Lifecycle Management 01.07.-04.07.2018, Torino, Italy.

[Eos18] **EOS (2018):** Datenaufbereitung & Prozesssoftware für die Additive Fertigung. Online: https://www.eos.info/systeme_loesungen/software_datenaufbereitung-und-prozesssoftware.

[Gib10] **Gibson, I.; Rose, D. W.; Stucker, B. (2010):** Additive Manufacturing Technologies – Rapid Prototyping to Direct Digital Manufacturing. 1. Edition. Springer, New York Heidelberg Dordrecht London. doi: 10.1007/978-1-4939-2113-3.

[Gur14] **Gurpal, S. B., Parlad kumar (2014):** Methods to Improve Surface Finish of Parts Produced by Fused Deposition Modeling. In: Manufacturing Science and Technology, 2014.

[Kag13] **Kagermann, H.; Wahlster, W.; Helbig, J. (2013):** Umsetzungsempfehlungen für das Zukunftsprojekt Industrie 4.0. Abschlussbericht des Arbeitskreises Industrie 4.0. Hg. v. Promotorengruppe Kommunikation der Forschungsunion Wirtschaft – Wissenschaft und acatech. Online: https://www.bmbf.de/files/Umsetzungsempfehlungen_Industrie4_0.pdf.

[Kir10] **Kirchner, K.; Jäschke, H.; Franke, H.-J.; Vietor, T.; Grote, K.-H. (2010):** Mechanischtechnologische Eigenschaften generativ gefertigter Bauteile in Abhängigkeit von der Bauteilorientierung. In: RTejournal - Forum für Rapid Technologie 1, 2010.

[Pla15] **Plattform Industrie 4.0 (2015):** Umsetzungsstrategie Industrie 4.0 – Ergebnisbericht der Plattform Industrie 4.0. Online: https://www.bitkom.org/noindex/Publikationen/2015/Leitfaden/Umsetzungsstrategie-Industrie-40/150410-Umsetzungsstrategie-0.pdf.

[Ver14] **Verein Deutscher Ingenieure (2014):** VDI 3405 – Additive Fertigungsverfahren – Grundlagen, Begriffe, Verfahrensbeschreibung.