DEVELOPMENT OF AN ADDITIVE MANUFACTURING PROCESS FOR THE PROCESSING OF CONTINUOUS FIBER REINFORCED POLYMERS

Matthias Domm[1], Jonas Fischer[1] and Peter Mitschang[1]

[1]Institut für Verbundwerkstoffe, Technische Universität Kaiserslautern, Erwin-Schrödinger-Straße,
Gebäude 58, 67663 Kaiserslautern, Germany
Email: matthias.domm@ivw.uni-kl.de, Web Page: http://www.ivw.uni-kl.de

Keywords: additive manufacturing, fused deposition modeling, thermoplastics, continuous fiber reinforcement

Abstract

Additive manufacturing (AM) is an innovative approach for the manufacturing of very complex structures without the need of expensive tools. However, polymer parts manufactured by AM are limited in their achievable mechanical properties. In order to face this drawback, a concept was developed to process continuous fiber reinforced polymers with AM. In a comparison of competitive methods the Fused Deposition Modeling (FDM) was determined as the most suitable process for the integration of endless fibers. Following the results from the preliminary studies a new process – the Fiber Integration Fused Deposition Modeling (FIFDM) – was developed. The process is based on an impregnated prepreg-material consisting of a Polypropylene (PP) filament with a continuous unidirectional glass fiber (GF) reinforcement. In order to gain an even better degree of complexity the process was extended to place the extruded material in free space. Besides the conveying and the heating system also a cooling and cutting device was developed. In order to design the heating and cooling of the GF-PP material, a thermal simulation model was built.

1. Introduction

Additive manufacturing is an innovative approach to manufacture very complex structures without the need of expensive tools. Furthermore, additive manufacturing enables a high degree of flexibility in manufacturing. No time-consuming retrofitting measures are necessary. As a consequence, additive manufacturing experiences an increasing demand in industrial applications.

However, the additive manufacturing of polymers has one great disadvantage. The printed polymer structures are limited in their achievable mechanical properties. For this reason, printed polymer parts are only used as consumer goods and for prototyping. In order to face this drawback, polymer materials for additive manufacturing can already be reinforced with short fibers [1]. As a further consideration of this approach, this paper deals with the development of a novel process to reinforce 3D printed polymer parts with continuous fiber reinforcement.

There are several additive manufacturing processes for polymers like Stereolithography, the PolyJet-Process, Selective Laser Sintering and Fused Deposition Modeling [2]. All processes can be divided in radiation curing-, sinter- and extrusion-based processes. For the radiation curing and the sinter processes the raw polymer is in a liquid or powder state. This makes it very difficult to integrate endless fibers into the process and the finished part. However, the raw material for the extrusion process is a continuous polymer filament which is placed in continuous polymer strings. Therefore, the FDM process is well suited for the integration of endless fibers. The most common extrusion process is the Fused Deposition Modeling (FDM). Within this process a polymer filament is pressed through a heated nozzle where it is melted. The extruded material is then placed on a print bed, building up the required geometry layer by layer.

Excerpt from ISBN 978-3-00-053387-7

There are initial efforts concerning the integration of endless fiber reinforcement in the FDM process [3, 4, 5]. The disadvantage of the screened processes are slow process speeds and low fiber volume contents because of the impregnation of the fibers during the process [3, 4] or restrictions in producible geometries because of the shape of the semi-finished products used [5].
In this paper, the development of a novel process based on the FDM process – the Fiber Integrated Fused Deposition Modeling (FIFDM) – is depicted. The new developed process is facing the mentioned drawbacks of fiber integration into the FDM process. Beyond that, the process also enables to print the reinforced material into free space.

2. Equipment and Materials

For the development of the FIFDM process a 3D printer by German RepRap was used (Figure 1).

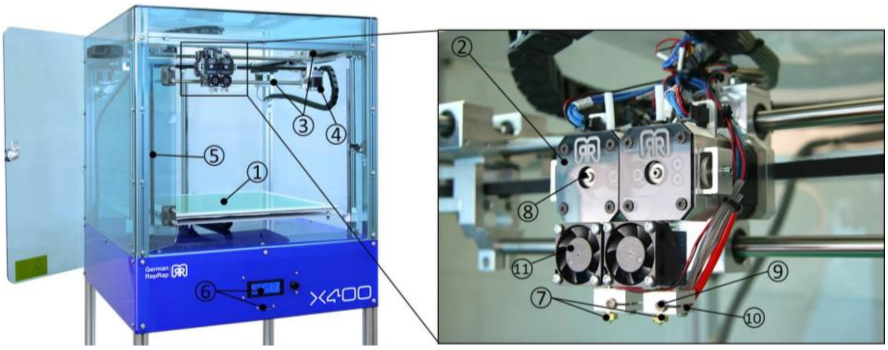

Figure 1. 3D-Printer X400 by German RepRap [6].

The printer operates on the principle of the hot melt extrusion FDM. The build platform amounts 400 x 400 x 380 mm^3 with a heatable print bed (1). The print head (2) can be moved along the x- and y-axis on shafts (3) driven by three stepper motors (4). The vertical movement is realized by lifting the print bed via threaded spindles (5). A PC or a SD card reader (6) with a panel can be used for the control of the printer. “Simplify3D” software was used to adjust the print parameters and generate a G-Code out of the given CAD data and parameters. The print head consists of two extruder units / hotends (7) that are working individually. Within the print head the polymer filament is pressed against a rotating roller (8) via a compression spring and therefore fed into a copper nozzle. The nozzle is heated by an electrically heated pin (9). The pin including a thermistor for the temperature control is mounted by a clamp (10) near the outlet of the nozzle. In order to keep the polymer filament at a conveyable temperature, the feeding unit can be cooled via air ventilation (11). The printer has a minimum resolution of 0.1 mm.

Common materials for the processing with the X 400 3D printer are polymer filaments consisting of ABS, PLA, PS or PVA with an initial diameter of 1.75 mm. For the development of the FIFDM Process a pre-impregnated Polypropylene (PP) filament with unidirectional endless glass fiber (GF) reinforcement was used. The PP-GF filament has an elliptic shape with a main axis of approximately 2.5 mm and a minor axis of 1.7 mm. The average void content was examined by a grayscale analysis of 5 microsections of the filament`s cross section in defined distances of 1.000 mm. It is about 9.2 Vol.-% with regard to the total volume and has a standard deviation of 2.8 %. The fiber weight content of the PP-GF filament is about 30 %. The melting temperature of the PP matrix is 166 °C. For the concept and feasibility studies also Polylactic acid (PLA) filaments and a carbon fiber roving (Grafil 34-700 24K) by Mitsubishi Rayon Carbon Fiber & Composite were used.

Excerpt from ISBN 978-3-00-053387-7

4. Conducted Research and Results

The results give an overview of the development of the FIFDM process, starting with the executed feasibility study to identify the best way for integration of continuous fibers into the FDM process. Moreover the development of necessary manufacturing devices including a thermal simulation is presented. Finally a study was carried out to identify optimized print parameters to validate the developed FIFDM process.

4.1 Integration of continuous Fibers

A concept and feasibility study was carried out in order to find the most promising approach for the integration of continuous fibers in the FDM process. Three different concepts were identified and investigated experimentally. The concepts and the results of the feasibility trials are shown in Figure 2.

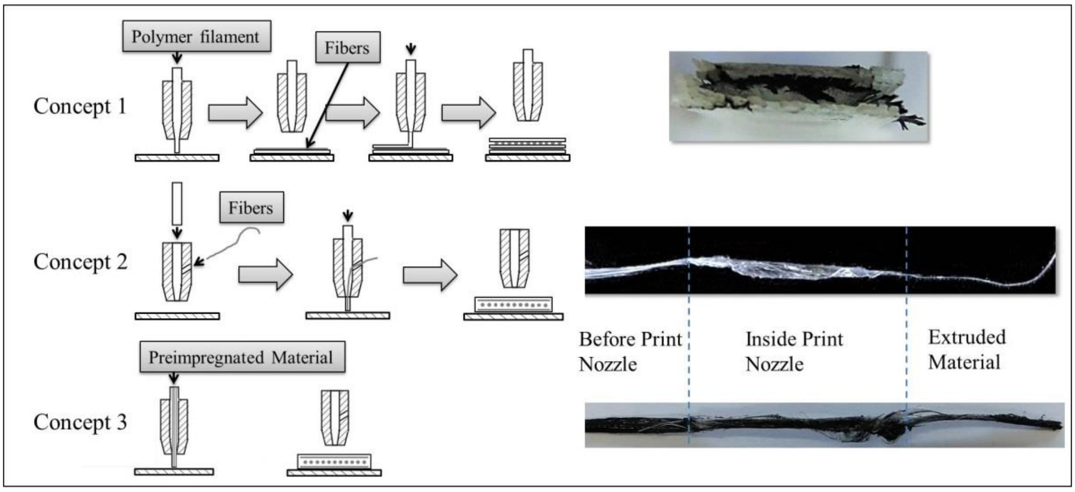

Figure 2. Concepts for Fiber Integration in the FDM process and results of feasibility studies.

The first concept shown in Figure 2 is based on the principle to place the fibers and the polymer separately. Due to the pressure applied by the distance of the print nozzle to the fibers and the print bed, the fibers are supposed to get impregnated. The second and third concept peruses the approach to integrate the fibers directly in the printing process. There are two options: the separate inlet of fibers and the polymer in the print nozzle (concept 2) or the use of semi-finished products like hybrid yarns or pre-impregnated filaments (concept 3).

For concept 1 a carbon roving (Grafil 34-700 24K) was spread to a width of 10 mm, placed on an already printed PLA layer and fixed with a Polyimide tape outside the print area. Another PLA layer was printed on the fibers. The results demonstrate that the pressure of the nozzle is insufficient for the impregnation of the fibers. For the feasibility trials of concept 2 and 3 the outlet of the print nozzle was increased from a diameter of 0.4 mm to 1.5 mm. Within the feasibility tests of concept 2, an additional diagonal hole for the inlet of the fibers was drilled into the side of the print nozzle. A glass fiber roving (1K) was inserted through the drilled hole during the print process with a PLA-filament. The fibers were pulled into the nozzle and showed a good impregnation quality. However, no sufficient print result could be achieved, due to a catching of the fibers in the nozzle which led to an immediate clogging of the nozzle. For the feasibility tests of concept 3, a pre-impregnated PP-GF filament (capture 3) was used. The tests showed that it is possible to convey the PP-GF filament through the nozzle. Also the impregnation quality was improved by the print process. A clogging of the nozzle also results in a fast interruption of the extrusion process. A sharp edge in the nozzle because of the change in cross section from inlet to outlet was identified to be one of the reasons for the fast clogging of the nozzle.

Excerpt from ISBN 978-3-00-053387-7

Based on the results of the feasibility trials, concept 3 was chosen for further development of the FIFDM Process. Concept 1 was excluded because of the insufficient impregnation of the fibers. Furthermore, concept 3 has several advantages against concept 2. Faster process speeds and higher fiber volume contents can be reached due to the fact, that the main impregnation step is not taking place during the print process. Besides, as the fibers are already orientated in the long axis of the prepreg material there is a lower risk of clogging of the nozzle.

4.2 Development of Manufacturing Devices

The feasibility studies revealed many drawbacks of the original 3D printer setup for the planned FIFDM Process. The PP-GF filament was heated very slowly and the regulation of the nozzle temperature was very slow. Furthermore, the fibers led to a clogging of the nozzle. Following the results of the feasibility studies, new manufacturing devices are necessary for the FIFDM Process.

In addition, several functions cannot be fulfilled by the initial setup of the 3D printer. A movement of the print head without conveying the PP-GF filament is not possible because of the endless fiber reinforcement. Also an in time solidification of the extruded material is necessary for the placing in free space. Based on the results of the feasibility studies the following requirements for the manufacturing devices of the FIFDM Process were made:

- Constant and fast printing
    - Fast heating of the processing material
    - Improvement of the temperature control of the print nozzle
    - Sufficient conveying pressure
    - No catching of the fibers in the nozzle
- Possibility of cutting the processing material
- In time solidification of the extruded material by a cooling system

The requirements result in a new development of the following manufacturing devices: Hotend, cutting device and cooling system. In the following only the results for the hotend and the cooling system are presented.

Figure 3 (left side) demonstrates the newly developed hotend of the print head. The nozzle has a through-hole with a constant diameter, so that the fibers do not dam on any edge. For a fast temperature regulation and a constant nozzle temperature, the thermistor is integrated into the print nozzle close to the processed material. The heating of the nozzle is implemented using a mineral isolated heating system. It is heated electrically with a power of 80 W and is wound over a large surface area of the nozzle. This enables a fast heating and a constant temperature range in the nozzle. The sleeves around the nozzle ensure the thermal insulation of the hotend from the environment. Hence, less heat is lost during the print process. This saves energy and minimizes the thermal fluctuations.

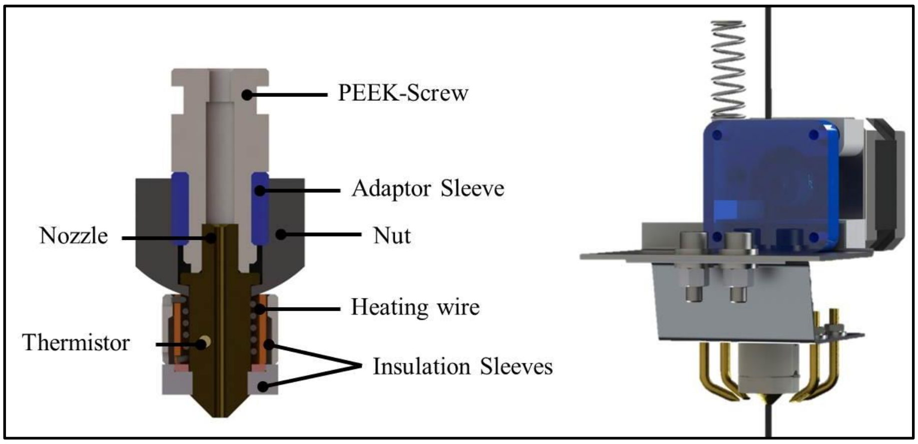

Figure 3. New developed Hotend (left) and Cooling System for 3D printer X 400 (right).

Excerpt from ISBN 978-3-00-053387-7

The cooling of the extruded material is implemented as an air cooling. The air flow is applied by air jets that are mounted on the print head. A concept with the 4 separated air jets was chosen because of the simple realization and the possibility to adjust them. The jets are connected to a compressed air supply via a throttle valve, in order to set the air flow velocity. The whole setup including the new developed hot end and the cooling systems is given in Figure 3 (right side).

4.3 Thermal Simulation and Analysis of the Temperature Profile

For the evaluation of the temperature control inside and outside the print nozzle a thermal simulation model was built. The heating of the filament in the nozzle has the biggest influence both on process speed and the robustness of the process. The cooling of the extruded material after the nozzle is important for the placing in free space. On the one hand the material must be flexible for the forming process. On the other hand, the extruded material has to be solidified in time, so that the printed structure has a sufficient stability. Therefore, a maximum solidification length was determined.

The simulation model was built by the use of the software "COMSOL Multiphysics" that enables to simulate the heat transfer with the help of the finite element method (FEM). A Computer Aided Design (CAD) model of the hotend and the PP-GF filament was implemented into COMSOL. The components were matched with the appropriate material data and types of heat transfer. For the simulation, all heat transfers were considered stationary. The components of the hotend transfer the heat via conduction. On the external surface of the hotend, the heat transfer takes place by natural convection and radiation. Between the nozzle and the PP-GF filament the heat is transferred by conduction. To simplify the simulation model, a continuous contact of the inner wall of the nozzle and the PP-GF filament is assumed. The extruded PP-GF filament cools down either by natural convection and radiation or in case of an active cooling by forced convection and radiation. Important material data for the simulation are the density, specific heat capacity, heat conductivity, heat transfer coefficient and emissivity. All these material properties are dependent on the temperature. In the following the determination of the material properties are demonstrated for the PP-GF filament.

The specific heat capacity was measured by differential scanning calorimetry (DSC) and interpolated linearly (Figure 4, left side). The heat conductivity of the GF-PP filament consisting of PP, GF and air was calculated with the help of literature values using the law of mixture (Eq. 1):

$$MP_F \cdot \varphi_F + MP_M \cdot \varphi_M + MP_A \cdot \varphi_A = MP_{GF-PP} \tag{1}$$

(MP: Material property; φ: Density; F: Fiber; M: Matrix; A: Air)

Because of its non-linearity, the calculation of the heat conductivity depending on the temperature was interpolated using a cubic spline (Figure 4, right side).

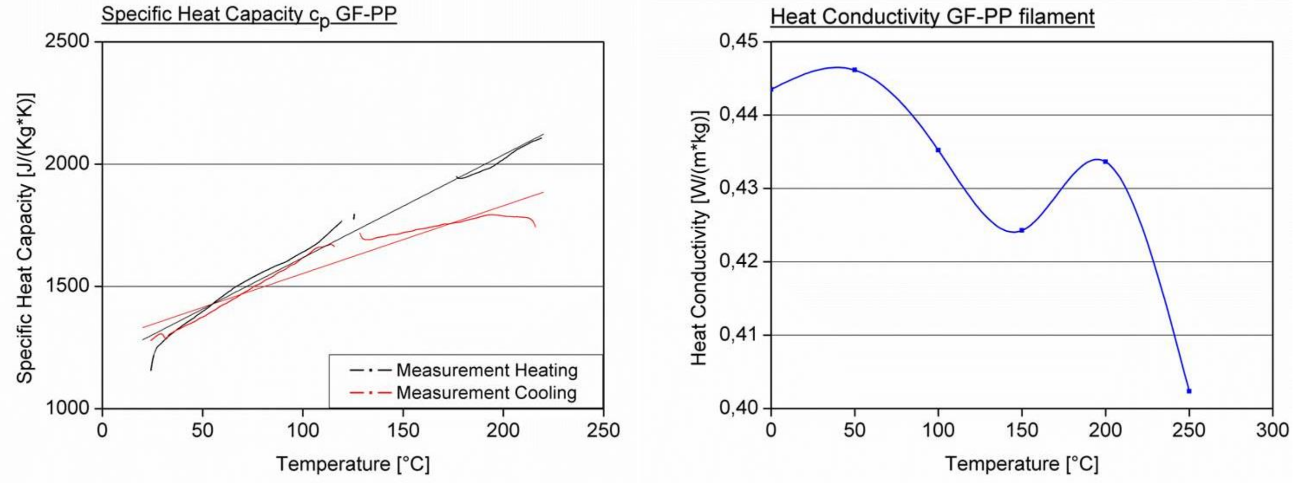

Figure 4. Determination of the specific heat capacity and heat conductivity depending on temperature.

Excerpt from ISBN 978-3-00-053387-7

The heat transfer coefficient was calculated with the help of the dimensionless Nusselt number for natural convection (Eq. 2) and forced convection (Eq. 3).

$$Nu_{nc} := \frac{h_m \cdot L_0}{\lambda} = f(Gr, Pr, \text{Geometry}) \tag{2}$$

$$Nu_{fc} := \frac{h_m \cdot L_0}{\lambda} = f(Re, Pr, \text{Geometry, Flow Direction}) \tag{3}$$

(Nu_{nc}: Nusselt number for natural convection; Nu_{fc}: Nusselt number for forced convection; h_m: middle heat transfer coefficient; L_0: characteristic length of heat transfer; λ: heat conductivity; Gr: Grashof number; Pr: Prandtl number; Re: Reynolds number)

The most important issues for the calculation of the convection are the geometry and the characteristic length of heat transfer. The geometry of the PP-GF filament is assumed to be cylindrical. The characteristic length outside the nozzle is changing during extrusion. As a consequence the heat transfer coefficient is not only dependent on the temperature but also on the extrusion length. In Figure 5 the calculation for the heat transfer coefficient for natural (left side) and forced convection (right side) is presented. To keep the simulation for the cooling system simple, a lateral air flow against the PP-GF filament is assumed.

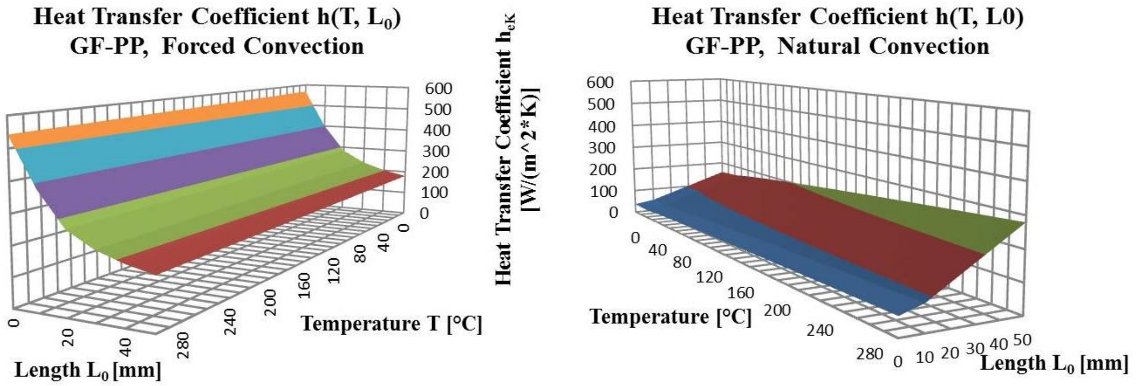

Figure 5. Calculation of the heat transfer coefficient for forced (left) and natural (right) convection depending on temperature and characteristic length.

The simulation for the cooling of the PP-GF material was verified by a temperature measurement during the extrusion process. The measurement was carried out by using a thermocouple which was placed in the PP-GF filament and a thermographic camera. In Figure 6, the setup for the verification trials is given. Both simulation and experimental measurement were carried out at an environmental temperature of 23 °C and a heat wire temperature of 210 °C. The verification was carried out with and without active cooling and for different process speeds and air flow velocities. An example is given in Figure 6, right side. It shows a good accordance between measurement and simulation.

Excerpt from ISBN 978-3-00-053387-7

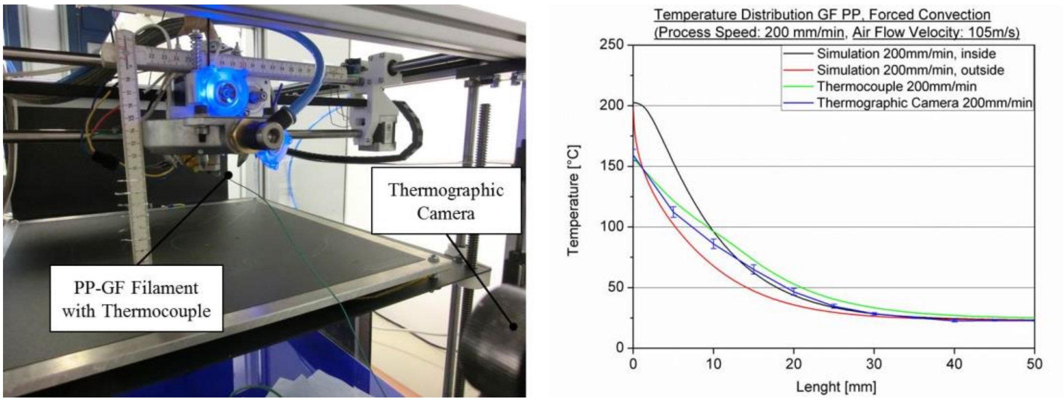

Figure 6. Setup for verification of simulation (left), comparison of experiment and simulation (right).

In order to design the cooling process, criteria have to be defined concerning the solidification of the molten PP-GF filament. Therefore, a maximum extrusion length for solidification was determined. For the stability of a printed structure a maximum deflection of 1 % was specified. In order to characterize the allowable stress for the maximum deflection of the PP-GF filament at a temperature of 210 °C, Dynamic-Mechanic-Thermal Analysis (DMTA) trials were carried. Hence, a maximum solidification length for the extruded PP-GF filament of 11 mm was calculated.

Several simulations were carried out to design the cooling process. Thereby, the cooling method, the process speed and the air flow velocity were varied. In Figure 7 some of the simulation results are summed up. The diagram compars the cooling curve of the PP-GF-filament for natural and forced convection depending on different process speeds. It reveals that without active cooling, the maximum solidification length of 11 mm cannot be achieved. With an active cooling the solidification criterion can be complied. The diagram on the right side shows cooling scenarios with different air flow velocities. It demonstrates that the air flow velocity can only increase the cooling effect up to a certain saturation limit, which is about 81 m/s for a process speed of 200 mm/min.

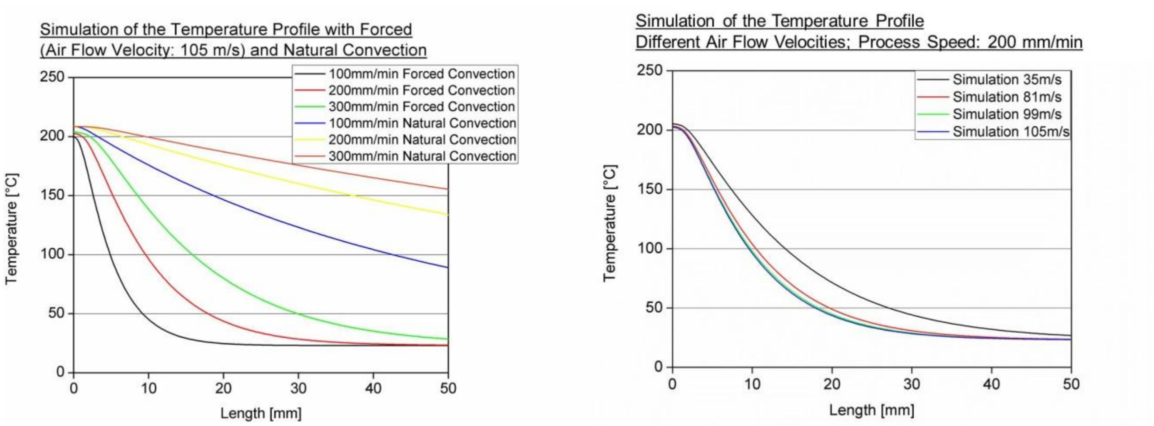

Figure 7. Simulation of temperature profiles of the extruded PP-GF filament.

4.5 Validation

With the new developed 3D printer setup and the PP-GF filament, process speeds up to 400 mm/min could be achieved. Reasons for the speed limit are the heat input and the through heating of the PP-GF filament. Also the inhomogeneous surface shape and inconsistent impregnation quality of the PP-GF material are limiting factors. In order to investigate the influence of the process speed on the impregnation quality, PP-GF filaments were extruded with different process speeds between 100 and 400 mm/min. The void content was determined by using grayscale analysis on microscales. The print

Excerpt from ISBN 978-3-00-053387-7

nozzle was heated up to 210 °C, which is 50 °C above melting temperature of the PP. Figure 8 shows the void contents for the different process speeds with the raw material as a reference. Three trials were carried out for each process speed. The diagram in Figure 8 demonstrates that the void content is increasing with higher process speeds with the exception of the results for 300 mm/min. A possible explanation is the inconsistent impregnation quality of the raw material.

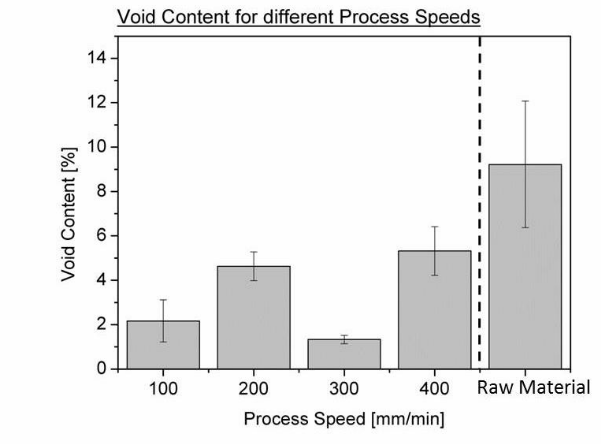

Figure 8. Void content of extruded material depending on process speed.

Finally, a demonstrator was printed with the presented setup. The adjusted process parameters for the manufacturing of the demonstrator were 100 mm/min extrusion speed, a nozzle temperature of 220 °C as well as an airflow velocity of the cooling jets of 35 m/s.

6. Conclusion

A conventional 3D printer based on the FDM method was modified for additive manufacturing of continuous fiber reinforced polymers. A pre-impregnated PP-GF filament was used as processing material. A new hotend as well as a cutting device was developed. With the creation of a thermal simulation also a cooling device was designed for the placement of the extruded material into free space. Finally, a demonstrator was printed successfully. In order to increase the process speed, future developments will have to deal with a faster heat transfer into the processed material as well as an improvement of the raw material for the new FIFDM process.

References

[1] F. Ning, et al.: Additive manufacturing of carbon fiber reinforced thermoplastic composites using fused deposition modeling. Composites Part B 80, 2015; 369-378
[2] Gebhardt, A.; Hötter, J.-S.: Generative Fertigungsverfahren: Additive Manufacturing und 3D Drucken für Prototyping - Tooling - Produktion. 4., neu bearb. und erw. Aufl., München: Hanser, 2013, ISBN 9783446436527
[3] Fischer, A.; Rommel, S.; Bauernhansl, T.: New Fiber Matrix Process with 3D Fiber Printer – A Strategic In-process Integration of Endless Fibers Using Fused Deposition Modeling (FDM). Digital Product and Process Development Systems. Springer Berlin Heidelberg, 2013, pp. 167–175
[4] Tyler, K.: Method and Apparatus for Continuous Composite Three-dimensional Printing, US 20140061974 A1, 2014
[5] MarkForged Inc.: https://markforged.com (07.04.2016)
[6] German RepRap GmbH: https://www.germanreprap.com/produkte/3d-drucker/x400/ (07.04.2016)

Excerpt from ISBN 978-3-00-053387-7