EVALUATION OF FIBER PLACEMENT STRATEGIES FOR THE IMPLEMENTATION OF CONTINUOUS REINFORCEMENT FIBERS IN SELECTIVE LASER SINTERING PROCESS

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ABSTRACT

Among engineering materials today continuous fiber reinforced polymers (FRP) show some of the highest stiffness and strength to weight ratios. To rival the traditional manufacturing methods of continuous FRP many investigations have sought to combine the outstanding mechanical performances of these materials with the freedom in design and the economic benefits of additive manufacturing (AM). This paper focuses on the fiber placement strategies and their interaction with Selective Laser Sintering (SLS) specific machine features. The goal is to develop and conduct test series to gain a deeper understanding of how the process, the polymer, and the reinforcement fibers interact. For this investigation different patterns of glass fiber rovings are embedded into specimens made from PA 12 on a Sintratec Kit printer. The rovings are put up onto a frame in varying patterns to be able to relate fiber tension and curvature as well as the stack height of intersecting rovings to the quality of embedding. Additionally the time of placement, the clamping and the interaction of the fibers with the recoater have been investigated. Based on these results an SLS printer with automated continuous fiber implementation will be developed in the future.

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1. INTRODUCTION

The material group of fiber reinforced polymers is relatively young and still subject to many investigations. But it has already opened up possibilities and applications that could not be realized with other materials. Especially the ratios of stiffness and strength to density are unrivaled and combined with the ability to tailor the mechanical properties along different orientations it is easy to see why composite structures are used in high end applications in many industries. However these outstanding performances come at a cost. Common to many manufacturing methods of continuous reinforced polymer parts are high costs due to a large amount of manual labor, a poor freedom of design and long lead times due to the necessity of molds. The field of polymer additive manufacturing shows its strength in exactly those three areas. On the other hand the mechanical properties of an additively manufactured part often lack behind its injection-molded or extruded counterpart [1]. By combining continuous fiber reinforcement with polymer additive manufacturing it is possible to cancel out the drawbacks and create a new method of manufacturing composite parts. As will be shown in chapter 2 a lot of research has been done to implement continuous fibers in extrusion based additive manufacturing processes and systems are already commercially available [2, 3]. For industrial applications the selective laser sintering process is considered a promising process due to the good mechanical properties, thermal stability, precision and surface quality [4].

In the research project FiberAdd conducted by the wbk Institute of Production Science at Karlsruhe Institute of Technology and funded by the Vector foundation (Stuttgart, Germany) the implementation of endless fibers in the selective laser sintering (SLS) process is examined. The overall project goal is the development of an SLS printer with an additional unit to automatically insert continuous fibers in the process to reinforce SLS printed polymer parts. This paper presents the evaluation of fiber path strategies with the aim to better understand the interaction between the continuous fibers, the SLS printer and the process. It addresses researchers in the field of continuous fiber reinforced AM and development engineers for AM equipment alike.

In this paper first the current state of the art in continuous fiber reinforced additive manufacturing is presented. Then the experimental set-up for the evaluation of the fiber paths will be explained. Afterwards the results for the test series are presented and discussed. Finally a conclusion and an outlook of the next steps is given.

2. STATE OF THE ART

In the following the current state of the art for the additive manufacturing with continuous fibers will be presented and analyzed. Previous investigations have mainly focused on three additive manufacturing methods that are either widespread and therefore well understood or show characteristics which makes it particularly easy to include continuous fiber reinforcement. Material extrusion is the most commonly used AM technique and makes up most of the research as well. The next common technique is stereolithography were also some work was done to introduce continuous fiber reinforcements to the process. Laminated Object Manufacturing (LOM) is not widely spread in neat polymer applications but due to its sheet feedstock continuous reinforcement fibers can easily be included in the process.

The most investigations have been made in the area of material extrusion and here especially in Fused Deposition Modelling (FDM). Baumann et al. suggested to cluster these methods by the point of fiber implementation [5]. The fibers can be brought together with the polymer matrix prior, inside, or after the extruding nozzle. Since the formation of the fiber-matrix interface is a crucial part of the print process a lot of work went into the development of the print nozzle itself. Fischer et al. argued that the fiber feeding could be done by the extruded polymer eliminating the need for a separate fiber-speed control system. Also, the interface formation would work best inside the hot nozzle where the polymer is at its lowest viscosity. They designed and manufactured a FDM nozzle via a selective laser melting process out of which the fibers and matrix material are extruded together [6]. Other works that were focusing on print nozzle development are Bettini et al., Li et al. and Yang et al. All of them combined the fibers and the matrix material inside the nozzle to form a fully reinforced part. Tests parts with a PLA matrix and aramid [7] or carbon [8] fiber reinforcement or an ABS/carbon combination [9] were printed and then the samples were tested mechanically to compare them to the neat matrix polymer. Li et al. went one step further and prepared a set of samples where the carbon fibers were coated in PLA prior to printing with the aim to investigate the influence of the interface formation. Several ways of placing the fibers inside the polymeric matrix have been tested and evaluated by Baumann et al. They found that only a fiber introduction after the nozzle would enable the machine to print a neat polymer and a composite with just one nozzle [10]. They investigated several ways of introducing a roving of carbon and glass fibers into a just printed bead of ABS using a modified Arburg freeformer. The fibers were laid down and overprinted, injected with a hot hypodermic needle, and sunken into the polymer with a solvent. The US American company Markforged offers with its Mark Two printer a machine capable of locally reinforce the build parts with continuous fibers. Unlike the approach of Baumann et al. the Mark Two uses two nozzles with one reserved for the neat polymer and the other to lay down a fiber rowing that is already impregnated with the matrix polymer. Using this commercial system or its predecessor Mark One, Dickson et al., Zhu et al. and van der Klift et al. investigated the mechanical reinforcement achievable with glass, carbon and aramid fibers [11–13].

Using stereolithography Karalekas and Antoniou fabricated dog-bone shaped tensile specimen from a polyurethane and epoxy based photo-polymer and embedded a nonwoven glass fiber mat into the middle layer. The specimens out of the epoxy based photo-polymer were reinforced with mats of four different basis weights while the polyurethane specimens only had two different mats. Generally the reinforcement effect increased with increasing basis weight except for the highest weight in the epoxy based photopolymer [14]. The second work of Karalekas used the same technique and test set-up but altered the materials investigated. An acrylic based photo-polymer was reinforced and tested with two glass and carbon nonwoven mats and an aramid mat [15].

Since 2D fiber mats and prepregs are the most used semi-finished products in composite manufacturing anyway it is the logical step to utilize them in LOM to additively manufacture composite parts. Klostermann et al. investigated the interface formation of glass fiber / epoxy prepreg. A post LOM consolidation cycle was necessary to reduce the void content and strengthen the layer interface [16]. To avoid the post treatment Parandoush et al. used a uni- and bidirectional glass fiber / PP prepreg composite sheet to manufacture their specimens. The individual layers were bonded by heating the surfaces of both strips with a CO2 laser and pressing them together with the consolidation roller [17]. In a later work Paradoush et al. used the same technique to manufacture multidirectional carbon fiber / PA 6 samples and did further investigations about the heat transfer inside the already build stack [18].

Table 1 summarizes the presented state of the art and shows which properties of continuous fiber reinforced additive manufactured parts have already been investigated. It can be seen that the mechanical properties of differently manufactured specimen have been investigated thoroughly. Also the interface between the fibers and the matrix polymer has been studied. However the combination of the SLS process and continuous fiber reinforcement is uninvestigated so far.

Table 1. Overview of the current state of the art in continuous fiber reinforced additive manufacturing

Process	References	Reinforcement material	Tested properties								
			Young’s modulus	Tensile strength	Strain at break	Stiffening	Flexural modulus	Flexural strength	Storage modulus	Interface	Porosity and voids
Material extrusion	Baumann, Scholtz et al. 2017	C, G	+	+	-	+	-	-	-	0	-
	Baumann, Sielaff et al. 2017	C	+	+	-	+	-	-	-	-	-
	Dickson et al. 2017	C, G, Ar	+	+	0	-	+	+	-	+	+
	Li et al. 2016	C	-	+	-	-	-	+	+	+	0
	Tian et al. 2016	C	-	-	-	-	+	+	-	+	-
	Fischer et al. 2017	C	-	-	-	-	-	-	-	0	-
	Bettini et al. 2017	Ar	+	+	+	+	+	+	-	0	-
	Yang et al. 2017	C	+	+	-	-	+	+	-	+	+
	Zhu et al. 2017	C	-	-	-	-	+	+	-	-	+
	Van der Klift et al. 2016	C	+	+	+	-	-	-	-	-	0
LOM	Klostermann et al. 1998	G	-	-	-	-	-	-	-	0	0
	Parandoush et al. 2017	G	+	+	+	-	+	+	-	0	+
	Parandoush et al. 2019	C	+	+	+	-	+	-	-	-	+
SL	Karalekas 2003	C, G, Ar	+	+	+	-	-	-	-	0	-
	Karalekas, Antoniou 2004	G	+	+	+	-	-	-	-	0	0

Symbols:
C – Carbon fiber, G – Glass fiber, Ar – Aramid fiber
+ fully examined, 0 partly examined, - not examined

3. EXPERIMENTAL SET-UP

This work wants to lay the base on which further research can develop a process to additively manufacture composite parts with the SLS process. To be able to automatically introduce continuous reinforcement fibers the interaction between the fibers and the process must be well understood. In contrast to the processes presented in chapter 2 the SLS process poses some unique challenges to the introduction of continuous reinforcement fibers. Unlike other common AM machines, a SLS printer shows many individually moving parts. This relative movement of polymer grains, machine parts and reinforcement fibers poses a challenge on process reliability. Hence the placement strategies of the reinforcement fibers need to take into account all the moving parts inside the build chamber. This interaction of the reinforcement fibers with parts like the recoater blade is crucial to maintain a stable and repeatable process. The main questions that are tried to be answered within the scope of this paper are the placement time of the continuous fibers, the achievable complexity of the fiber patterns, how well the fibers can be embedded in one layer height and whether fixation of the fibers after placement is needed.

3.1 Development of test series

The conducted experiments are split up in two test series differing in the timing of the fiber placement during the SLS process. In test series one the fibers are placed manually on top of an already sintered layer before the recoater applies a new powder layer. In the second test series a new layer of powder is applied first and then the fiber is placed manually, followed by the pass of the laser to sinter the material.

The objective of the first test series is to see how the recoater as well as the fresh powder moved by it would alter the position of a fiber roving placed on the build chamber. Different placements and fixation points make the fibers successively more vulnerable to the recoater movement. It is recorded how, and at which step in complexity the initial placement fails to be transferred to the final part. To evaluate if the location of the roving was changed a simple specimen is designed with a cutout in the middle and a notch on either side. The roving can be placed exactly over the notches and the cut-out. So after printing the movement is easy to determine by its position visible at the cut-out. Figure 1 shows the steps in fiber-pattern complexity and the shape of the specimen. To secure the rovings in place two sets of fiber brackets are printed on the machine itself. With these the roving can be secured either parallel or perpendicular to the recoater movement.

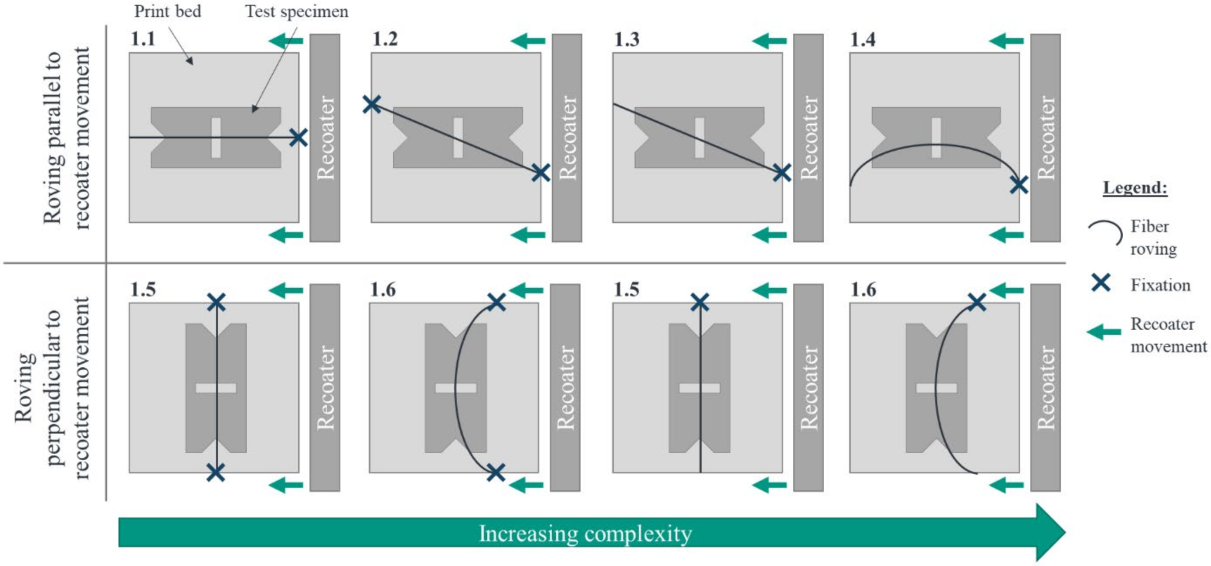

Figure 1. Test set-up for test series one with increasing complexity to the right

The main goal of the second series of tests is to investigate how well a roving can be embedded into the part when it is introduced to the powder bed after the recoating step. The target parameters here are the stability of a roving's fixation inside one layer and the maximum stack height of a fiber pattern before it cannot be securely embedded in one layer anymore. Additionally the effect of curvature and tension of the fibers on embedding and interface formation was analyzed. In order to be able to place the rovings in the powder bed a frame was printed onto which they could be stretched and placed on top of the powder surface. Four different fiber patterns were designed to investigate the above mentioned research goals. The first two tests 2.1 and 2.2 are focused on how well the roving can be embedded within one layer height and how strong this connecting is. Test 2.3 investigates the maximum fiber stack height that can be securely embedded, and 2.4 investigates the effect of curvature and fiber tension on the way the roving is embedded. For this second test series the specimen shape is a simple rectangular plate. Figure 2 shows the specimen shape, the frame and the different fiber patterns for the test scenarios of the second test series.

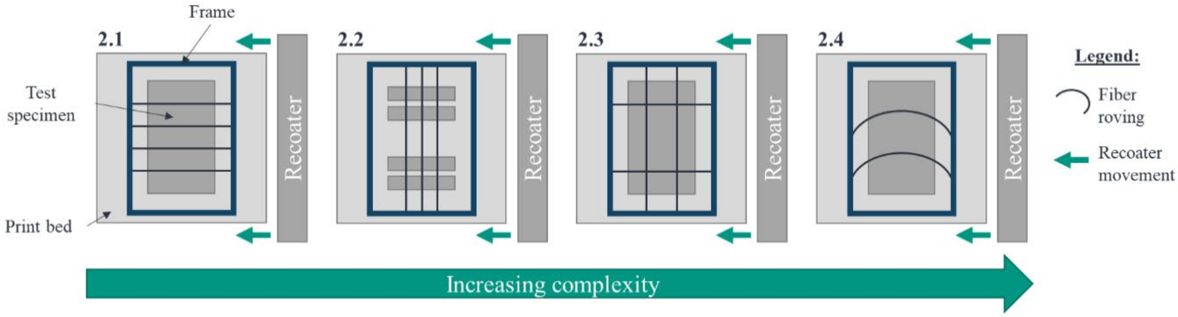

Figure 2. Test set-up for test series two with increasing complexity to the right

3.2 Experimental procedure

The previously described test series were conducted with a Sintratec Kit desktop SLS printer from the company Sintratec (Brugg, Switzerland) shown in Figure 4. For the experiments the materials and process parameters shown in Table 2 were used.

Table 2. Material and process parameters for conducted test series

Material	
Fiber	Glass fiber roving D450 60 tex (Fulltech Fiber Glass Corp.)
Powder	PA 12 Black Powder (Sintratec)
Process parameters	
Heat up temperature powder surface	150 °C
Heat up temperature build chamber	140 °C
Print temperature powder surface	170 °C
Print temperature build chamber	140 °C
Laser speed	500 mm/s
Layer height	0.1 mm

The Sintratec Kit is a low-cost desktop SLS printer widely used in academia and research. It comes with an own closed control system and a software called Sintratec Central to preprocess the proprietary control code for the machine. The adjustment of process parameters and process steps is very limited and restricted to basic settings like the print temperature, laser speed and layer height. After the start of the print job no further control of the printer is possible. After slow heating of the build chamber (approx. 1.75 hours) and powder bed preparation, the sintering of the part is done in a cyclic manner. This cyclic procedure consists of recoating fresh powder from the reservoir, infrared heating of the new layer to print temperature and sintering with the laser. After the last layer the printer cools down for another 1.5 hours. In order to be able to manufacture the planned composite specimen on the machine a specific experimental procedure has been developed as a workaround solution.

For the first test series the specimen is created as a .stl file with half of the plate thickness and then imported to the Sintratec Central software. At the start of each new experiment the machine is always loaded with fresh powder and heated up. After the heat-up the lower half of the specimen is printed classically. Right after the last layer of the part is scanned by the laser and molten, the machine is stopped via the emergency stop button. The printer is opened, and the roving placed manually on the last layer. This positions the roving onto the consolidated polymer, ready to spread the next powder layer over it. The time during which the machine was open is kept as short as possible since the process chamber would lose a lot of heat which in turn could alter the results. After preparing the build chamber in one of the ways shown in Figure 1 the machine is closed, and the same print job is started again. Because every new print job starts with the preparation of a hot powder base this step has to be skipped to not burry the first half of the specimen and the roving under the powder. By starting the new print the recoater spreads a layer of powder over the already build specimen and the suspended roving. It is recorded how the fibers behave under the influence of the recoater and how many layers it took to completely embed the roving into the part. After the specimen is printed for the second time, the printer performs its normal cooldown program. Figure 3 shows the step-by-step procedure of this first test series.

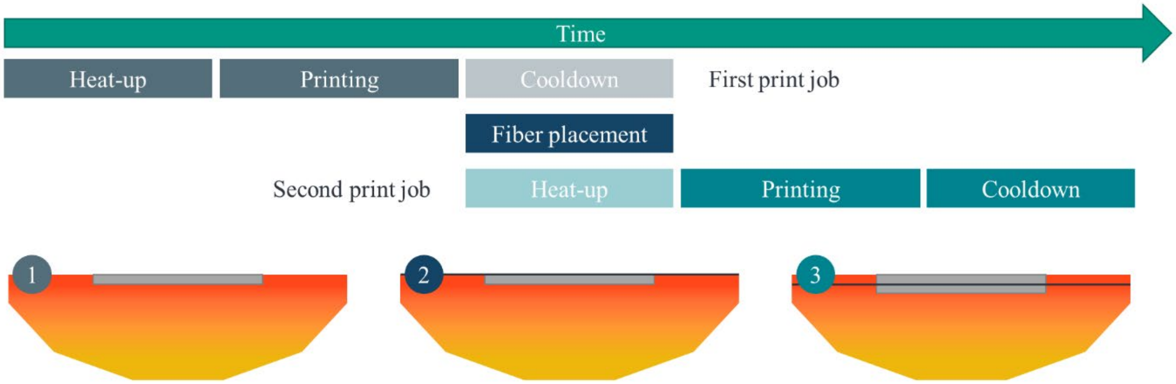

Figure 3. Specific step-by-step test procedure for the first test series

The control problem for the second test series is different. The Sintratec Kit always executes the previously described three basic build steps successively. After the initial powder bed recoat the infrared lamps heat it up to the pre-set sinter temperature and then the laser scans the cross-section of the part to be printed. In order to only heat and scan a previously applied powder layer the blade of the recoater must be detachable. This still allows the printer to perform the recoat operation but the frame or the recoater does not come in contact with the powder bed or any device sitting on top of it. Similar to the first test series also the specimens for the second test series are printed in two steps. The first print is performed in the known way but this time the printer is not stopped after but before the sintering of the last layer. This leaves the last coat of the powder bed untouched. The machine is opened and the recoater blade is removed. Then the frame with the fiber rovings is placed onto the powder bed according to the set-up shown in Figure 2 and the machine is closed again. Just like in the previous test series, the time when the machine was open is kept at a minimum to reduce the temperature drop inside the process chamber. With the machine closed a new print job is started according to the test set-up. Again, the powder bed preparation is skipped manually. The printing of one layer always starts by moving the recoater and spreading new powder. Due to the detached recoater blade only the recoater frame moves without applying fresh powder. Hence the powder bed with the fiber frame is not disturbed (cf right side of Figure 4). Then the infrared lamps bring the powder surface back to sintering temperature and the laser scans the cross-section. After that the print is manually aborted and the machine is given time to cool down.

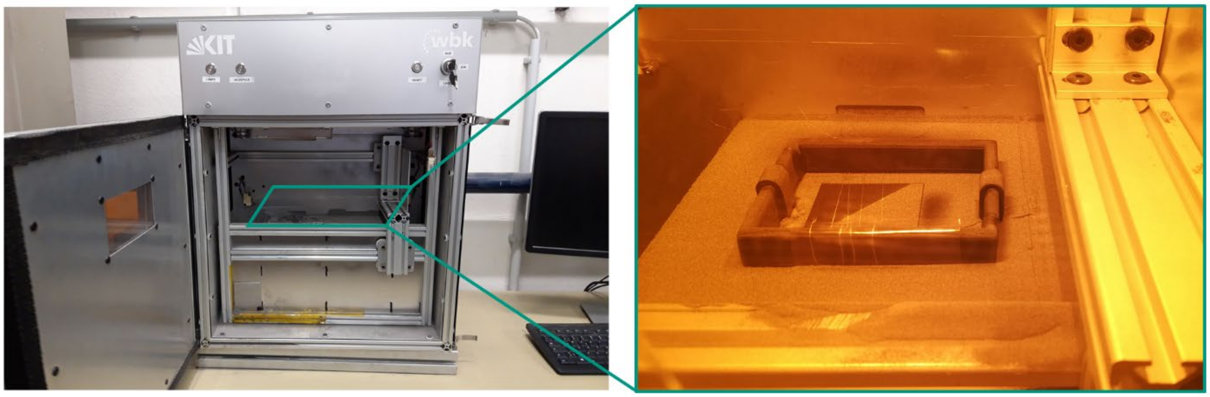

Figure 4. Sintratec Kit desktop SLS printer used for test series (left side) and view of build chamber during print of second test series after insertion of the frame (right side)

4. RESULTS

4.1 First test series

In the first test series the roving was placed manually prior to the application of fresh powder for a layer. For the two roving orientations the complexity of the set-up was raised until the fibers could not be embedded in the part anymore and their positions were altered by the movement of the recoater. As the complexity in the tests increases no more complex test has been carried out after a failed test scenario.

For test 1.1 the intended location of the fiber and in the actual part differ only a little bit (cf. Figure 5). This small displacement was not caused by the recoater blade but during the manual placement of the roving in the first place. Due to the alignment of the recoater movement and reinforcement fibers the roving is tensioned by the recoater and therefore keeps its position parallel to the recoater movement. During the recoating the blade and the fresh powder stretches the roving out and covers it in powder. This is enough to prevent it to be touched and moved again by the retracting recoater blade. After the first laser scanning the roving is secured on the part and none of the following steps could alter its position. In test 1.2 we can also observe a good placement of the fiber inside the test specimen. In the center of Figure 5 we can see that the fiber is well tensioned inside the test specimen. The small position error can also be attributed to the manual placement of the fiber.

For both test 1.1 and 1.2 we can observe a good integration of the fiber into the polymer. The embedded roving is completely embedded in the sintered powder which has been applied on it. The bonding is strong enough to withstand a slight manual pull on the fiber. However it is yet to find out if the bonding mechanism is purely mechanical or if it relies on adhesion forces as well.

In test 1.3 the roving was only fixed on one side but orientated at an angle to the recoater movement. In this test scenario the recoater blade significantly changed the position of the roving during the print process as can be seen on the right of Figure 5.

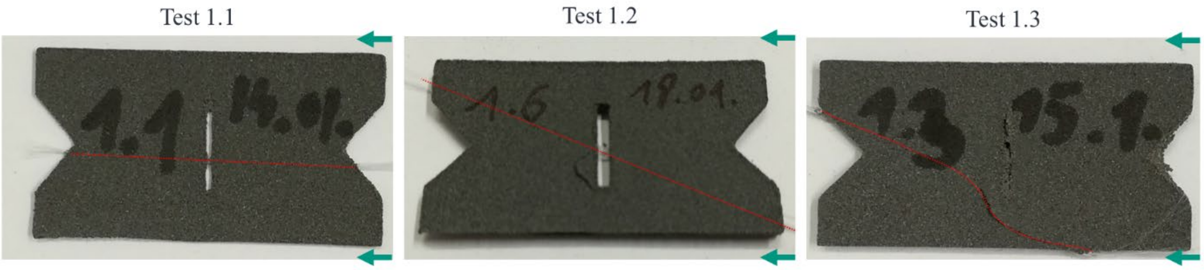

Figure 5. Red highlighted roving position of test specimen with roving parallel to the recoater movement (direction of recoater movement shown by arrow)

The roving in test 1.5 the positioning of the roving is at the desired place in the center of the test specimen without a negative effect of the recoater movement. Also, here the small deviation was due to an error in the manual placement of the roving.

The position of the roving without tension in test 1.6 on the other hand was highly altered by the recoater movement. In Figure 6 on the right side we can see the position of the roving in the finished specimen is curved to the opposite direction of its initial manual placement. This is caused by a movement of the roving by the retracting recoater blade. It can also be seen, that the two halves of the specimen did not align perfectly, which is caused by the recoater moving the lower half of the specimen.

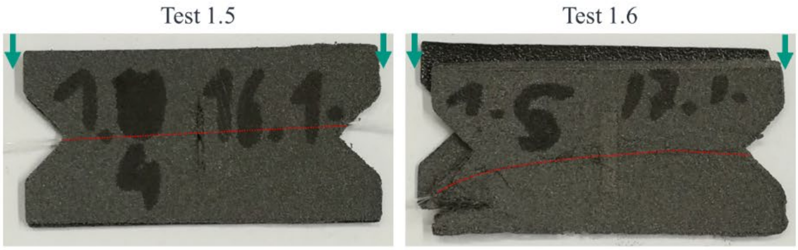

Figure 6. Red highlighted roving position of test specimen with roving perpendicular to the recoater movement (direction of recoater movement shown by arrow)

We can conclude from this first test series that the implementation of fibers before applying new powder for a layer fails if the fiber alignment is not straight and without tension. Without the fixation of the fiber the recoater moves the fiber in an uncontrolled manner. On the backstroke the recoater blade picks the rowing up and pulls it out of the powder again. This leads to the roving loosely lying on top of the powder bed during the laser scanning. Due to the fibers low weight and inherent spring only a few points actually contact the powder bed so no real interface can be established.

4.2 Second test series

In the second test series the rovings were placed manually after the application of fresh powder for the layer. The roving was fixed at both ends by the frame and kept under tension (except test 2.4).

Figure 7 shows that in test 2.1 the roving is embedded into the polymer layer after one sintering step. The fibers are not completely covered by the matrix, but bridges of molten polymer particles have formed over the roving can be observed. The fibers are not bonded to the matrix by the formation of a strong interface but rather by mechanically locking them in place through powder particles forming bridges over the roving.

Test 2.2 is a similar scenario than 2.1 but with the fibers placed perpendicular to the recoater movement. Here the roving is only fixed in specimens of 5 mm width. We can observe that enough polymer bridges have formed over this short distance, so the fibers are secured in place as in test 2.1.

In test 2.3 fibers were placed in two directions to observe the behavior at fiber intersections. It can be seen that the lower roving is attached to the specimen through the polymer bridges like in the previous scenarios, but the upper roving is not attached at all (cf. right side of Figure 7).When the mechanism of bonding is not changed the thickness of the complete fiber stack up cannot exceed the height of one layer or issues in fiber fixation can occur. Because no real interface can be formed the roving must be fully embedded to secure it to the specimen plate.

The final test 2.4 without tension in the rovings shows no embedding or fixation of the rovings at all. The specimen plate is not attached to the rovings, but lines of unmolten powder were the fibers blocked the light from the laser can be seen.

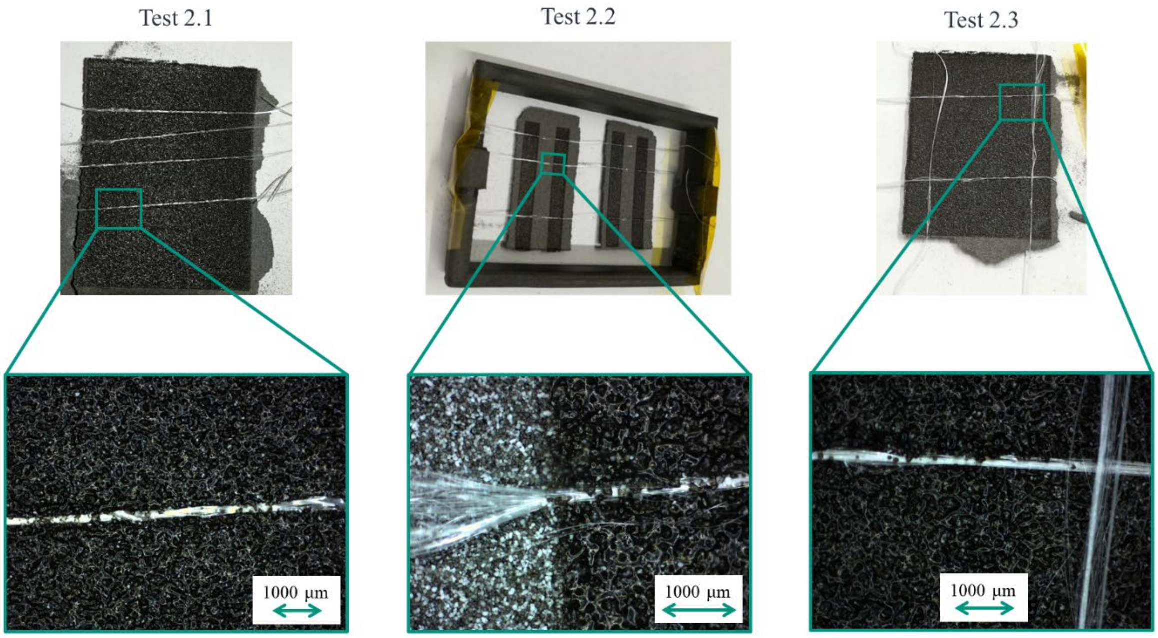

Figure 7. Results of second test series with fiber placement after powder application

For test series two it can be summarized that a placement of a single layer of fibers without intersection is possible after the application of powder for a new layer. The fixation of the fibers is achieved by small randomly formed polymer bridges rather than a real bonding of the roving to the polymer. An intersection of fibers is not possible with the used layer height due to the increased height and the resulting contact with the recoater.

5. CONCLUSION AND OUTLOOK

From the results presented in this paper conclusions can be drawn for fiber placement strategies. First, it can be stated that the fibers need to be under tension during interface formation. Regardless whether the reinforcement is introduced before or after the application of fresh powder for a layer the fibers will not remain in the intended place during the sintering step without tension. This also means that no curved fiber path can be realized with the tested approach. Therefore additional trials and development have to be made in order to overcome this issue. For instance a curve could be approximated by short straight segments under tension instead.

It was shown that fibers can be sufficiently embedded in one layer height to act as a fixation point in a fiber placement strategy. Even without a dedicated thermoplastic sizing and adapted laser paths the roving was securely and repeatably fixed to the specimen. This proves that a fiber reinforcement within the SLS process is possible. However with the mechanical fixation mode seen here the fiber stack height is limited to the layer thickness of the process.

As mentioned before, this work contributes to the development of a SLS printer with an additional unit to automatically insert continuous fibers in the process to reinforce SLS printed polymer parts. The results of the presented work have shown that an automated fiber placement is needed to allow further process development and an improvement of the achievable fiber paths. The following steps in this field are the investigation of interface formation, the development of more complex fiber paths for a load-dependent part design and the design and implementation of a fiber placement module inside an SLS printer. After the technical implementation the complete system needs to be characterized and an appropriate selection of materials and process parameters needs to be found.

6. REFERENCES

[1]. P. Pinter; S. Baumann; C. Lohr; A. Heuer; L. Englert & K.A. Weidenmann. “Mechanical Properties of Additively Manufactured Polymer Samples Using a Piezo Controlled Injection Molding Unit and Fused Filament Fabrication Compared with a Conventional Injection Molding Process” *Solid Freeform Fabrication Symposium*. Austin, Texas, USA. August 13-15, 2018.

[2] *Markforged Carbon Fiber Filament*. Markforged. 03 Jan 2020 <https://markforged.com/materials/carbon-fiber>

[3] *Arburg: Freeformer 300-4X für faserverstärkte Bauteile - Zusätzliche Achse ermöglicht lokale Bauteilverstärkung - Praxisbeispiel: Individuelle Handorthesen für die Medizintechnik*. 21 Oct 2019. Plasticker – the home of plastics. 03 Jan 2020 < https://plasticker.de/Kunststoff_News_36078_Special_k19_Arburg_Freeformer_300_4X_fuer_faserverstaerkte_Bauteile___Zusaetzliche_Achse_ermoeglicht_lokale_Bauteilverstaerkung___Praxisbeispiel_Individuelle_Handorthesen_fuer_die_Medizintechnik?special=k19>

[4] Wendel, B.; Rietzel, D.; Kühnlein, F.; Feulner, R.; Hülder, G.; Schmachtenberg, E. „Additive Processing of Polymers“, *Macromolecular Materials Engineering* 293 (10) (2008): 799–809. DOI: 10.1002/mame.200800121.

[5]. Baumann, F.; Sielaff, L. & Fleischer, J. “Process Analysis and Development of a Module for Implementing Continuous Fibres in an Additive Manufacturing Process”, *SAMPE Europe Symposium*. Stuttgart, Germany. November 14 – 16, 2017. Society for the Advancement of Material and Process Engineering.

[6]. Fischer, A.; Rommel, S. & Bauernhansl, T. “New Fibre Matrix Process with 3D Fibre Printer - A Stragic In-Process Integration of Endless Fibres Using Fused Depostion Modeling”, *IFIP TC 5 International Conference, NEW PROLAMAT 2013*. Dresden, Germany. October 10-11, 2013.

[7]. Bettini, P.; Alitta, G.; Sala, G. & Di Landro, L. “Fused Deposition Technique for Continuous Fiber Reinforced Thermoplastic”, *Journal of Materials Engineering and Performance* 26(2) (2017): 843–848. DOI: 10.1007/s11665-016-2459-8.

[8]. Li, N.; Li, Y. & Liu, S. “Rapid prototyping of continuous carbon fiber reinforced polylactic acid composites by 3D printing”, *Journal of Materials Processing Technology* 238 (2016): 218–225. DOI: 10.1016/j.jmatprotec.2016.07.025.

[9]. Yang, C.; Tian, X.; Liu, T.; Cao, Y. & Li, D. “3D printing for continuous fiber reinforced thermoplastic composites. Mechanism and performance“, *Rapid Prototyping Journal* 23(1) (2017): 209–215. DOI: 10.1108/RPJ-08-2015-0098.

[10]. Baumann, F.; Scholz, J. & Fleischer, J. “Investigation of a New Approach for Additively Manufactured Continuous Fiber-reinforced Polymers“, *Procedia CIRP 66* (2017): 323–328. DOI: 10.1016/j.procir.2017.03.276.

[11]. Dickson, A. N.; Barry, J. N.; McDonnell, K. A. & Dowling, D. P. “Fabrication of continuous carbon, glass and Kevlar fibre reinforced polymer composites using additive manufacturing“, *Additive Manufacturing* 16 (2017): 146–152. DOI: 10.1016/j.addma.2017.06.004.

[12]. Zhu, P.; Li, S.; Ashcroft, I.; Jones, A. & Pu, J., “3D Printing of continuous fibre reinforced thermoplastic composites“, *21st International Conference on Composite Materials*, Xi’an, China. August 20-25, 2017.

[13]. van Der Klift, F.; Koga, Y.; Todoroki, A.; Ueda, M.; Hirano, Y. & Matsuzaki, R. “3D Printing of Continuous Carbon Fibre Reinforced Thermo-Plastic (CFRTP) Tensile Test Specimens“, *Open Journal of Composite Materials* 6(1) (2016): 18–27. DOI: 10.4236/ojcm.2016.61003.

[14]. Karalekas, D. & Antoniou, K. “Composite rapid prototyping. Overcoming the drawback of poor mechanical properties“, *Journal of Materials Processing Technology* 153-154 (2004): 526–530. DOI: 10.1016/j.jmatprotec.2004.04.019.

[15]. Karalekas, D. E. “Study of the mechanical properties of nonwoven fibre mat reinforced photopolymers used in rapid prototyping“, *Materials & Design* 24(8) (2003): 665–670. DOI: 10.1016/S0261-3069(03)00153-5.

[16]. Klostermann, D.; Charthoff, R.; Graves, G.; Osborne, N. & Priore, B. “Interfacial characteristics of composites fabricated by laminated object manufacturing“, *Composites Part*

A: Applied Science and Manufacturing 29(9-10) (1998): 1165-1174. DOI10.1016/S1359-835X(98)00088-8.

[17]. Parandoush, P.; Tucker, L.; Zhou, C. & Lin, D. “Laser assisted additive manufacturing of continuous fiber reinforced thermoplastic composites“, *Materials & Design* 131 (2017): 186–195. DOI: 10.1016/j.matdes.2017.06.013.

[18]. Parandoush, P.; Zhou, C. & Lin, D. “3D Printing of Ultrahigh Strength Continuous Carbon Fiber Composites“, *Advanced Engineering Materials* 21 (2019). DOI: 10.1002/adem.201800622.