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In-situ consolidation of additively manufactured continuous fiber reinforced material: Technical approach and results

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Abstract. Additive manufacturing (AM) of continuous fiber reinforced composites (CFC) is becoming increasingly important in the field of lightweight construction. The major advantage lies particular in the automated manufacturing process and in the production of complex geometries. Most work was done with traditional fusion filament fabrication (FFF) and the lack of separate consolidation units. AM CFCs produced in this manner have shown increased consolidation-related volumetric flaws -i.e. deconsolidation defects decreasing mechanical performance. The presence of deconsolidation defects, normally indicates either poor process parameters selection or inadequate in situ consolidation. Recently, there were several efforts in modifying the FFF of CFCs to minimize deconsolidation defects through in situ thermo-mechanical pressing. However, there are only limited fundamental knowledge on the in situ thermo-mechanical consolidation of FFF-CFCs. The present paper analyses the stated problem and proposes ways to decrease deconsolidation in FFF CF-PA6 laminates. For this purpose, we used a self-developed FFF 3D Printer coupled with a thermo-mechanical pressing unit. The influence of extrusion-, consolidation temperature, printing speed and in situ consolidation pressure on laminate microstructure and flexural strength was investigated. A comparison with FFF laminates printed in a common 3D printer was performed. The controlled 3D printing consolidation process leads to a homogeneous distribution of fibers in the matrix material and to an improvement of the material parameters of the reinforcing composite.

Introduction

Due to the efforts to increase efficiency, minimize costs and reduce emissions, many branches of industry are undergoing radical changes. Lightweight engineering through 3D printing provides measures towards these goals, as it allows several effects to be achieved at the same time: a) Lightweight engineering saves emissions in transport industry. b) In combination with 3D printing, it makes it possible to produce complex lightweight components economically in a resource-saving manner. c) Due to its flexibility and automation possibilities, 3D printing can be used particularly well in the field of structural element design. When high-performance materials such as composites are used, it becomes interesting for the automotive and aerospace industries. 3D printing is increasingly recognized as a technical solution in these areas and will significantly change the way complex, ultra-lightweight components are manufactured.

The company Markforged (MF) was a pioneer in industrial use of AM CFC and produces components with considerable complexity. The mechanical properties of materials produced with this technology are lower than those of conventionally produced fiber composite components, such as those produced with automated tape laying or cast polymer molding technology. One of the reasons for the weakening properties is the high void content in the laminate caused by a poor choice of printing process parameters and resulting an inhomogeneous distribution of fibers in the matrix material [1,2]. An insufficient utilization of the reinforcing fibers is the result and can lead to premature failure of the component. In a preliminary investigation, the influence of consolidation in 3D printing of CFC was shown. It has been found that increasing the contact pressure on the molten filament can lead to a reduction in voids in the laminate and an improvement in mechanical properties [3-6].

Increased consolidation is not feasible with standard 3D printing technology of fiber composites. What would be required is a time-delayed additional consolidation in the range of the crystallinity temperature of the matrix material. This is the aim of the present work, which describes a technology for in-situ consolidation.

For this purpose, a self-developed consolidation printer (CP) and the MF technology were used. The following approach is considered: Specimens of the used material are printed with the CP technology under controlled conditions at the crystallinity temperature and compared with the test specimens of the MF technology. Material tests and microstructure analyses are carried out and compared with each other. By preparing microsections of the specimens, a closer look inside the structure of the material is obtained which defines the basis for further understanding in terms of its homogeneity.

Materials and methods

Parameters on the behavior of the matrix material as a function of time and temperature are not part of the manufacturer's specifications. For this purpose, preliminary tests had to be carried out, which are necessary for a controlled thermal consolidation of the material. The preliminary examination of the filament, the technical approach of the MF printer and CP, the test specimens and the defined process parameters are documented below.

Filament material.

The thermoplastic prepreg used in this study was a 1K roving of continuous carbon fiber, which was pre-impregnated with a nylon matrix (CF-PA6) [7]. The CF-PA6 filament has a diameter of about 0.389 [mm] and a fiber volume fraction f of 35.0 ± 0.1%. This value is in accordance with results reported by other authors, such as He et al. [8]. After a differential scanning calorimetry (DSC) analysis the glass transition temperature, crystallinity temperature and the melting temperature of the CF-PA6 prepreg material as well the PA6 matrix material of MF without reinforced fibers was determined (see Table 1).

Table 1. Results of DSC measurement.

Material	Glass transition temperature [C°]	Crystallinity temperature [C°]	Melting temperature [C°]
CF-PA6	66	169	225
PA6	54	163	242

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CFC 3D printer.

To analyze the conventional consolidation strategy of 3D-printed CFC, the mechanical technology as well as the software of a Mark-two printer of MF was used. The mechanical construction of the MF printer has been reported by the manufacturer and in many papers [9-11]. For a consistent printing quality, some adjustments are made according to the manufacturer: The distance between the nozzle tip and the printer has to be set with a shim leveling to 0.127 [mm] by a constant nozzle temperature to 250 [°C]. A new continuous fiber filament role with a low moisture content was used for printing the test samples. To ensure a good hold of the printed pattern on the print bed, an adhesive glue, recommended by the manufacturer, was applied on the print bed. The default parameters of MF at the slicer software Eiger are used as printing condition for the CFC CF-PA6 material print.

Consolidation printer.

For a detailed consolidation study a consolidation test bench was developed and constructed. All technical functions for continuous fiber 3D printing are similar to MF. The printing bed is moving in x-, and y-axis direction and the printer head is moving in z-axis direction with a trapezoidal Tr8 x 1.5 [mm] thread. The filament feeder, cutter, hotend and nozzle are MF components. With this technical setup, the process and the printing quality of MF can be reproduced. In order to implement the influence of the consolidation, an in situ thermomechanical consolidation roller is installed after the nozzle tip. There is no mechanical coupling installed between the nozzle and the consolidation unit. Therefore, the fiber can only be deposited in x-direction and no curved paths are possible with this setup. Each path must be deposited individually to obtain the part width of the three-point bending specimen (see Fig. 2 CP Specimen).

With a load cell (HBM PW4M), the current consolidation pressure in the printing process was measured. The diameter of the consolidation roll is 26 [mm] and is tempered with a 12 [V] 30 [W] cartridge heater. The rotation of the consolidation roller is transmitted to the CFC filament by the contact pressure. The distance between printing nozzle and the consolidation role is adjustable and is in this study about [mm]. The consolidation roll is on the same level as the nozzle tip and applies a contact force about 5 [N] to the filament.

The printer was prepared with an open controller board from GT2560 Ref A+ and can be operated with an open-source slicer software. Various process parameters such as speed, temperature and the layer height can be changed additionally. These parameters were controlled with the Repetier-Host software (Hot-World GmbH & Co. KG). The G-code for the specimen geometry is developed independently in-house and imported into the control system of Repetier-Host. The schematic process of the consolidation test bench is shown in Fig. 1.

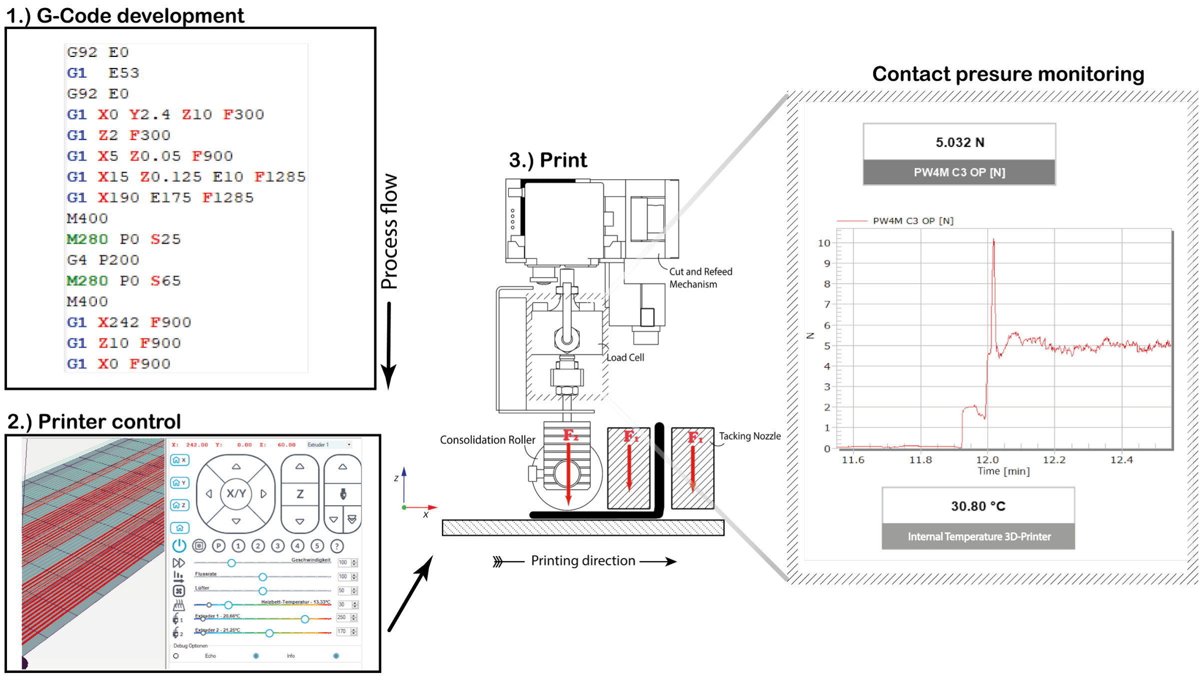


Fig. 1. Schematic process of the consolidation test bench.

Specimen geometry and mechanical testing.

The material tests were carried out using three-point bending tests. The dimensions are 60 x 15 x 2 [mm] (length x width x thickness) following the testing standards ISO 14125 with a line offset of approx. 0.9 [mm]. The pure PA6 coating and CFC loops at the reversal points produced by the MF printing process are removed. The printing strategy as well as the printing composition of the MF and the CP specimen is shown in Fig. 2. Each specimen consists of 14 layers, with 15 lines per layer. The layer height, printing speed and nozzle temperature for both printers were chosen of the default settings of MF and is listed in Table 2. The consolidation force on the CP samples is about 5 [N] for each line, while simultaneously maintaining the matrix material at its crystallinity temperature of 170 [°C] (see Table 1). In order to obtain reliable results of the mechanical tests, eight test samples are produced per series.

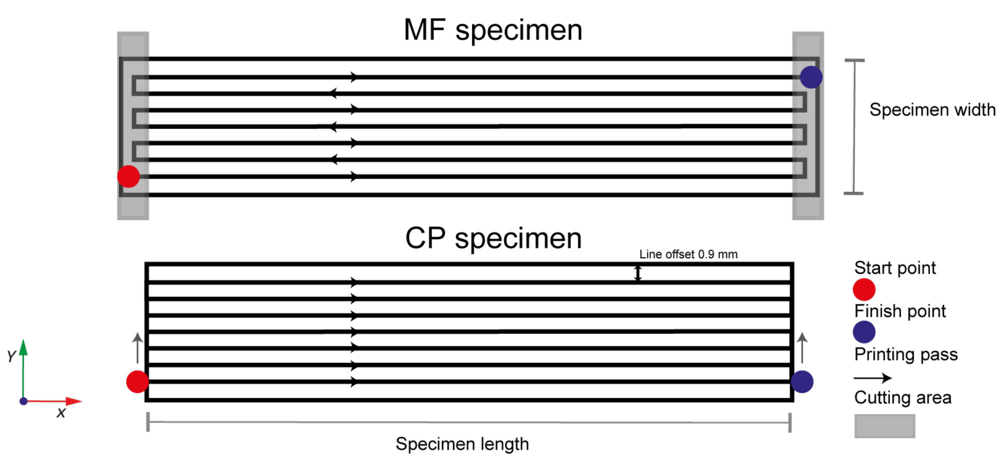


Fig. 2. Print path in a layer of MF and CP.

The three-point bending tests were conducted on a universal testing machine Z020 (Zwick/Roell). The manufacturer's software testXpert II was used on the testing machine to initialize the test parameters and record the test data.

Process parameters and data analysis.

The process parameters of the CP printer were controlled and measured with the Repetier-Host software and are listed in Table 2. The control of the process parameters of the MF system was realized with the Eiger software and contains the standard parameters of MF (see Table 2).

Table 2. Printing conditions.

Variation	Fiber-orientation	Nozzle height [mm]	Consolidation force roller [N]	Printing-speed [mm/s]	Nozzle tip temp. [C°]	Consolidation roller temp. [C°]	Printing bed [C°]	Internal temperature 3D-printer [C°]
CP	0°	0.127	5	15	250	170	30	30
MF		0.127	-	15	250	-	-	30

An HBM QuantumX MX1615 interface was used for data acquisition of consolidation pressure and chamber temperature of the CP printer. The visualization and data storage were implemented with the software catmanEasy. To ensure the correctness of the measured data, a reference measurement was made using a high-resolution balance.

Microstructural analysis.

The binocular microscope Axio Lab.A1 with a 5X and 20X magnification (Zeiss, Oberkochen) was used to observe the fiber distribution as well as the void content of the test specimens. The images were taken with a 2.0 MP Pixel-Fox digital camera (Dietermann & Heuser Solution, Greifenstein-Beilstein) and processed with the manufacturers image measuring software.

Results

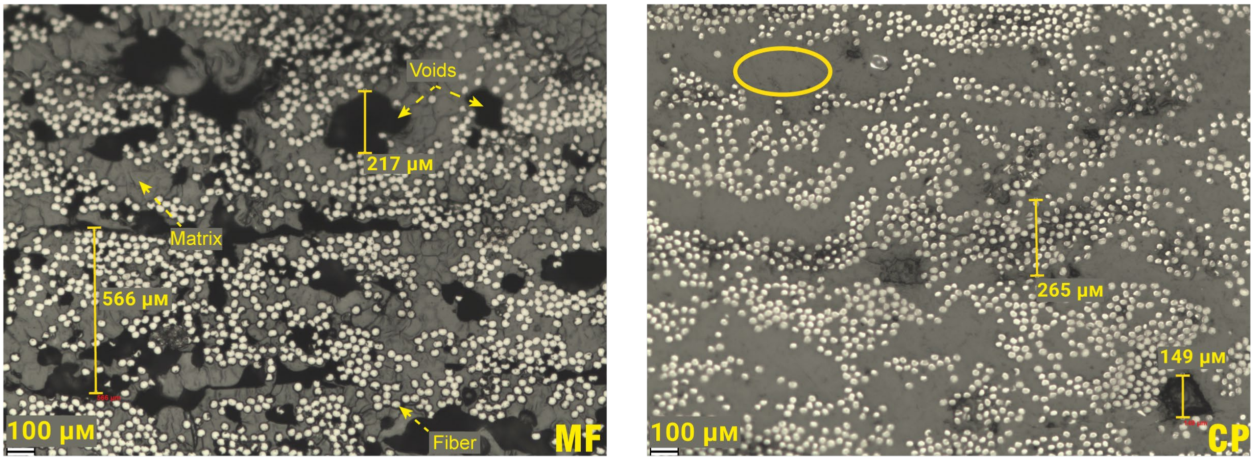
In order to be able to assess the quality of the laminate, detailed information is required on the micro- and macrostructure as well as the respective mechanical properties of the laminate. For this purpose, the following investigations were carried out.

Cross-sectional observation.

Typical examples of cross-sectional microscopy images of the MF and CP specimens in the direction perpendicular to the fiber are shown in Fig. 3.

The 3D printed laminates of MF (see Fig. 3a), show a lot of micro and macro voids in the laminate. Larger voids have a size of approximately 200 [µm]. Individual layers with insufficient intimate contact are to be recognized in the observation. Layers in the laminate have a height of approximately 600 [µm] and indicate a deconsolidation mechanism in the printing process. Further, horizontal cracks indicate a delamination. The fibers show a good distribution in the matrix material.

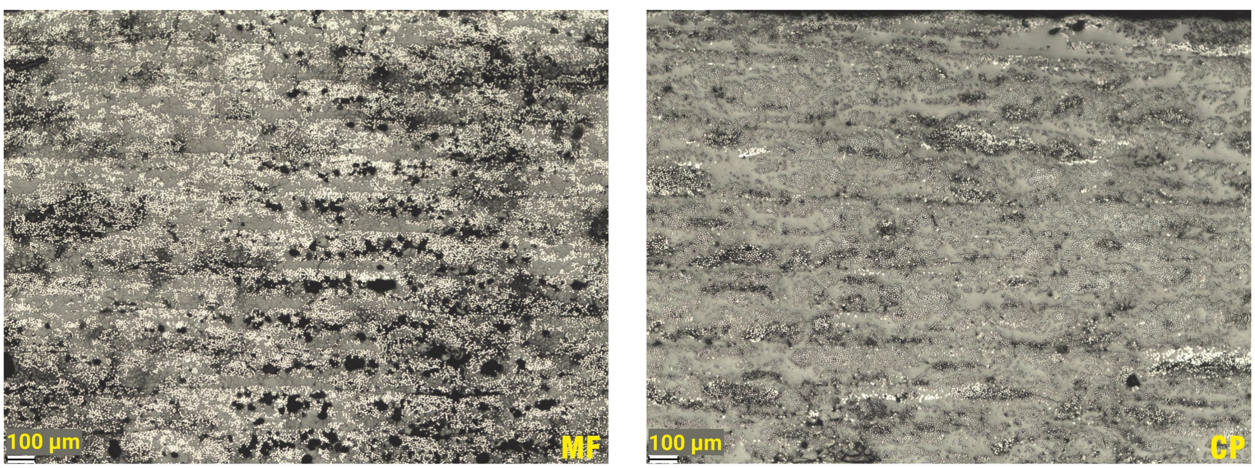
On the right side on Fig. 3 the laminate of the CP test bench specimen is shown. This laminate has hardly any micro and macro voids. Individual layers are partially marked with larger matrix areas (see Fig. 3b yellow circle). A reduction in deconsolidation is shown in the region of the joining zone of each layer. The layer heights are significantly lower compared to the MF samples and are about 270 [µm] (see Fig. 3b).



a) b)

Fig. 3. Microscopy images of a cross-section perpendicular to the fiber direction with a 20X magnification of a) MF and b) CP laminate with 14 layers.

Fig. 4 shows the laminates of MF and CP in 5X magnification. An expected high number of voids and delamination in the MF composite can be seen (see Fig. 4a). CP has a uniform mesostructure with a low proportion of voids (see Fig. 4b).



a) b)

Fig. 4: Microscopy images of a cross-section perpendicular to the fiber direction with a 5X magnification of a) MF and b) CP laminate with 14 layers.

Bending test results.

Fig. 5 shows the bending strength a) and the bending modulus b) of unidirectional CFC specimens printed using MF and CP, respectively. The average values of bending strength and bending modulus are 38.9 ± 3.2 [GPa] and 518.1 ± 42 [MPa] for MF specimens, and 39.2 ± 3.9 [GPa] and 610.9 ± 32 [MPa] for CP specimens, respectively. The CP specimens show an 15% improvement in bending strength and about 1% improvement in bending modulus.

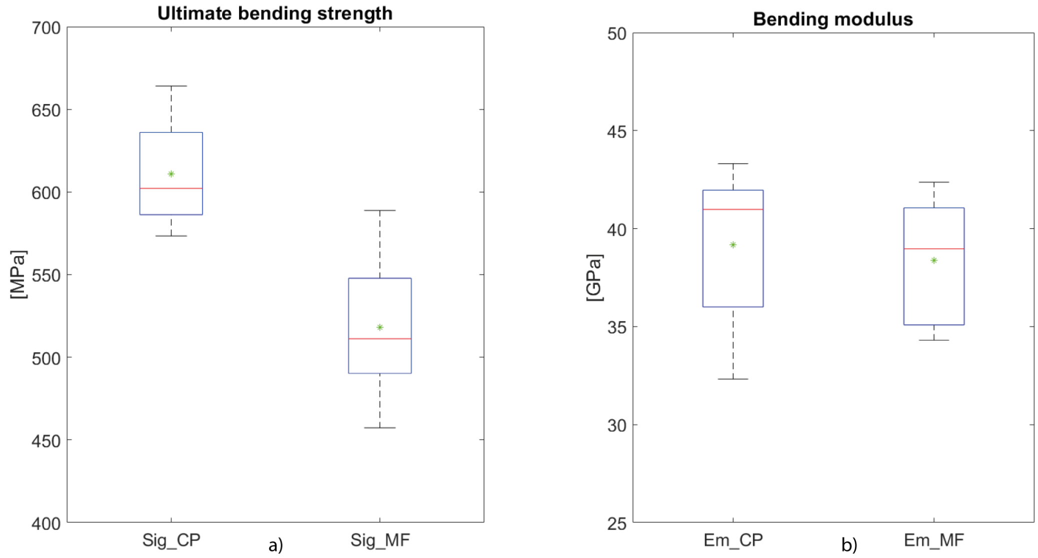


Fig. 5. Comparison of ultimate bending strength a) and bending modulus b) of the MF and CP technology.

Summary

In this study, a technical approach of a time-delayed thermal-mechanical consolidation of 3D printed CFC was investigated firstly. After a DSC analysis of the CF-PA6 material the glass transition temperature, crystallinity temperature and the melting temperature was determined. The CP test bench had the same technical approach as the MF printer, except for an additional in-situ thermo-mechanical consolidation unit. In the printing process, a force of 5 [N] was applied on the filament at a temperature close to the crystallinity temperature of the matrix material. In order to analyze the effects of in-situ consolidation in terms of microstructure and mechanical properties, a comparison was made with the printed test samples of MF technology.

The adopted process of in-situ consolidation has shown an improvement of the mechanical properties and the microstructure (15% for the bending strength and 1% for the bending modulus). In addition, the reduction of the void content was found in the CP composites in comparison to the MF composites. In summary, the MF laminates show clear signs of deconsolidation, while the CP composites are much more homogeneous.

In a next study, the influence of in-situ consolidation on the voids in the laminate and on the distribution of the fiber matrix will be analyzed. For this purpose, a traditional 2k full factorial design of experiment (DoE) will be used to investigate the different influences of the process parameters and microstructure of the 3D printed CFC laminate.

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